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Southern Meridiani Planum - A candidate landing site for the first crewed mission to Mars

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ABSTRACT

Astronauts working on the surface of Mars have the capability to explore efficiently, rapidly, and flexibly, allowing them to perform a wide range of field investigations. NASA has begun an open international process to identify and evaluate candidate locations where crews could land, live and work on the martian surface, beginning with the First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars in October 2015. Forty seven sites were proposed, including several at or near the Meridiani area, the subject of this paper. We consider the Meridiani area an excellent candidate for the first missions to Mars. It is accessible, safe, contains potential water resources in the form of poly-hydrated magnesium sulphates, has diverse science features with high likelihood of meeting all science goals, has other potential resources and potential for further longer-ranged exploration. The presence of hardware from previous missions will be of benefit to studies of materials to martian conditions, assessing the effectiveness of historic planetary protection strategies, and engaging public interest. Lastly, parts of the Meridiani region have been well studied from the surface by the *Opportunity* mission, providing ground truth for orbital data. As one of the best documented regions of Mars this will allow a "Go where you know" approach for the first crewed missions, especially with regard to safety, trafficability, and water resource potential.

1. Introduction

Astronauts working on the surface of Mars have the capability to explore efficiently, rapidly, and flexibly [27]. This allows them to perform a far wider range of field investigations with larger scientific payloads than can be performed by any conceivable robotic mission [73,105]. Instead of instrument payloads of a few kg to a few tens of kg, we expect a crewed mission to deploy a far wider range of instruments, tools, and surveying instruments, drill many metres beneath the surface and have substantial on-board laboratory equipment in the habitat to aid field interpretations and selection of samples for Earth return. Much greater masses of returned samples can be achieved, hundreds of kg for crewed missions [31], as opposed to hundreds of grams [55] for un-crewed sample return.

Site selection criteria methodologies for un-crewed missions have been extensively developed. Recent examples of this process include the MSL/*Curiosity* [41,45], Mars Exploration Rover [43], and *Phoenix* [4] missions. The greatly enhanced capabilities of crewed missions and the high level of socio-political engagement with any crewed landing, a somewhat modified methodology emerged at the First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars (first HLS^2 workshop, [14]. It was held at the Lunar and Planetary Science Institute in Houston on October 27–30th 2015. Forty seven sites were proposed, including the southern Meridiani Planum area discussed in this manuscript [23].

The destinations for crewed Mars missions considered at the first HLS^2 workshop were referred to as Exploration Zones (EZs). Each EZ is a collection of Regions of Interest (ROIs) that are located within approximately 100 km of a centralized Landing Site (LS). The ROIs are of two types: (1), scientific regions (SROIs) and (2) regions suitable for the development or maturation of capabilities and resources necessary for a sustainable human presence (RROIs). The EZ also contains

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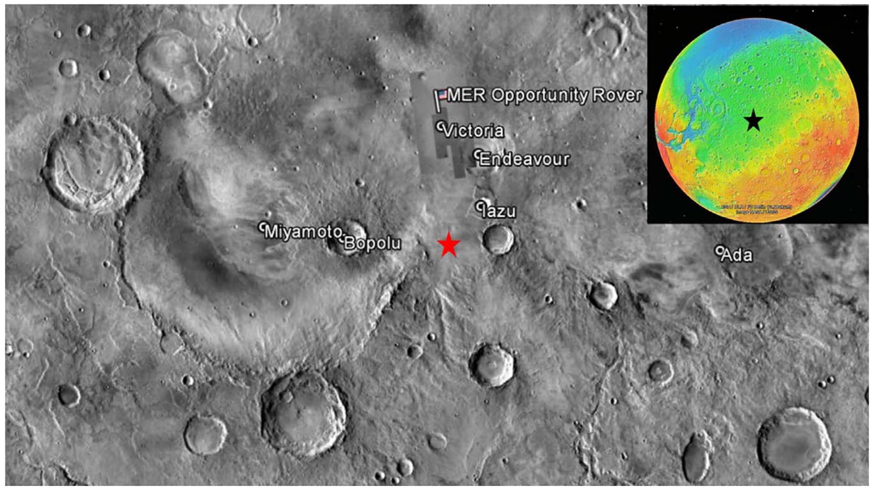

Fig. 1. Southern Meridiani landing site, marked by black star in inset and red star on main map. Meridiani plains are visible to the north, and Meridiani highlands to south. Google Earth images based on MOLA (inset) and THEMIS daytime infra red data. Image width 420 km.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

landing (LS) and a habitation (HS) sites that will be used by multiple successive human crews during missions to explore and utilize the ROIs within the EZ, thus setting the stage for a permanent station [69].

This implies a most significant methodological change to the site selection procedure than employed on previous missions. These missions focused on "hypothesis testing" (*senso* [85] with regard to individual features [43,53]. On a crewed mission there are multiple SROIs each being roughly equivalent to a target for a rover mission such as MSL/Curiosity or the MERs. The SROI would potentially provide a testing ground for multiple hypotheses regarding Mars and its history. This approach is perhaps more realistic with respect to actual exploration, as it allows for the testing of hypothesis bundles (*senso* [32]) as anticipated by [17]. One consequence being that mission objectives should no longer be expressed in terms of testing individual hypotheses, but in terms of the potential of the SROIs to address multiple questions.

Our proposed LS [23] lies in the southern Meridiani Planum region (Fig. 1). It is proximal to several other proposed EZs [25,108], also [81]. Together, these EZs comprise the Arabia Terra group [48]. In this paper we present a more detailed description of our Meridiani Planum EZ (with minor adjustments following conference feed-back) and justification of our reasons for considering it as an EZ for the first human missions to Mars.

2. Outline

In this paper we will cover the following issues:

- Meridiani station mission goals
- Mission requirements
- Previous landing site work in or near the area
- Location
- Landing zone

1. Safety
2. Infrastructure siting
3. Water availability
4. Science ROIs
5. Other resource ROIs
6. Indicative traverses

- Inner exploration zone

1. Safety
2. Water availability
3. Science ROIs
4. Other resource ROIs
5. Other features
6. Indicative traverses

- Outer exploration zone

1. Safety
2. Water availability
3. Science ROIs
4. Other resource ROIs
5. Other features
6. Indicative traverses

- Discussion

1. Safety
2. Water resources
3. Science goals
4. Other resources
5. Previous mission hardware and sites
6. Public engagement
7. Precursor missions
8. Common objections
9. Follow-on mission potential

- Conclusions

3. Meridiani station mission goals

The Apollo program to the moon began with Apollo 11 demonstrating the first technical achievement of landing on the moon but also achieved some science investigation goals. Successive Apollo missions each built on the previous mission technical achievements that included long duration foot traverses (Apollo 12 and 14) followed by rover traverses to undertake successively more ambitious science achievements. The science data obtained in the Apollo missions was very significant and is still being investigated 40 years later [27].

We argue that crewed missions to Meridiani will be somewhat analogous to Apollo, in that technical achievements will be coupled to the science accomplishments, and like Apollo, the science investigations will become more ambitious and dominant with each successive phase of the mission. However, the exploration scope of even the first mission to Mars – 540 sols, probably 70 or more EVAs in total – will dwarf that of all the Apollo missions combined. Even allowing for several weeks adaptation to Martian conditions and extensive engineering tasks establishing the station on the surface, the first month on the martian surface will see all Apollo records with respect to EVAs, time on the surface, instruments deployed, and distance covered, eclipsed. Multiple missions to the same LZ will allow assembly of a more complete Mars station – "Meridiani Station".

With these observations in mind we suggest that the goals of the first mission to Meridiani are to be prioritised as follows:

1. Safety – *Injury or loss of life could cripple a Mars mission*. The First Landing mission must land, carry out technical and scientific operations, and return safely. Safety concerns must dominate over all others.
2. Habitat construction – *People first need a safe haven in a hostile environment*. Assembly of Meridiani station commences with the First Landing mission. Habitat modules will be connected and buried (if applicable), and solar power generator farms estbalished. These objectives will be met with the needs of the First Landing mission foremost, but also with those of future missions in mind.
3. Water resources – *Water extraction is a fundamental requirement in most Mars mission architectures*. Demonstrating water extraction from regolith that can satisfy the needs of foreseeable future missions will be top priority for the first mission. The First Landing workshop argued that the landing site selected must have known water availability prior to the first mission. Successful water extraction will have to occur before the first crew arrives to ensure this occurs.
4. Science – *Exploring Mars's surface for the benefit of humanity*. We argue meeting threshold science return be a requirement for the First Landing mission particularly to cover the event of future missions being delayed or cancelled. The First Landing mission threshold science objectives would investigate the EZ threshold SROIs requirements [69]. The threshold criteria for NASA robotic missions, generally agreed by the science community (see for example the proposed 2020 rover mission, [77], is new science undertaken that justifies the expense of the mission. This approach is encapsulated by [69] for crewed missions. In addition, we expect the First Landing science will include field surveys in rovers and deep drilling covering most of the EZ, collecting broad science data assisting planning future detailed investigations, and providing confidence in the technologies deployed for science for future expeditions.
5. Other resources – *Planning for 'go to stay'*. The First landing mission will identify other potential resources with priority to those than can be utilised with minimal processing and power.
6. Follow up mission potential – *Planning for the long term*. the Meridiani area is suitable for either a stand-alone mission or for a succession of missions, especially given investigation into potential resources. These may lead to the establishment of a permanent station.

4. Mission parameters

4.1. Operational requirements

The mission parameters were set out at the first HLS^2 workshop [69] and summarised in Table 1. While not directly linked to specific mission architectures, they are broadly consistent with what a number of studies, e.g. [109,30,31], or [29] suggest could be achieved. The overall surface mission capabilities of all these missions meet the goals laid out by [105,12,73]. [87] does not use *In* Situ Resource Utilisation (ISRU) but has a large surface payload with similar capability. Another study [89] also eschews ISRU but has a much smaller effective payload for Mars exploration. It would be unlikely to meet the required goals as defined here.

Table 1
Current exploration zone requirements for landing crewed missions (modified from [69] with additional categories from [41,45] for MSL).

#	Parameter	Requirement
1	**Latitude**	50°N to 50°S
2	**Elevation**	Below +2 km altitude
3	**Landing zone radius**	< 100 m
4	**Blast zone radius**	~1 km
5	**Landing site area**	25 Km^2
6	**Exploration radius**	~100 km
7	**Duration**	~540 sols
8	**Relief (landing site)**	100 – 130 m over 1000 m baseline (MSL)
9	**Slope (landing site & habitat zone)**	< 15° over 20 m length scale (MSL)
10	**Slope (pressurised rover route)**	< 30°, width ~5x greater than rover width (~15 m)
11	**Roughness (lander)**	Probability of rocks > 0.55 m in randomly sampled 4 m^2 should be < 0.50%. (MSL)
12	**Roughness (pressurised rover)**	< 20% coverage by obstacles > radius of rover wheel (0.55 m)
13	**Load-bearing surface**	High thermal inertia, low albedo, not dominated by dust or sand
14	**Exclusion zones**	Areas up to 5 km radius for locating hazardous infrastructure (e.g. nuclear reactors)
15	**Surface winds**	< 15 m/s (steady); < 30 m/s (gusts); steady winds never exceed 40 m/s (MSL)

4.2. Science requirements

The Scientific objectives for crewed missions to Mars have been classed as astrobiology, atmospheric sciences, and geosciences [12,73]. These diverse investigations would take full advantage of the capabilities of astronauts to perform complex field science [50], [27]. These are shown in Table 2 (from [12]. Threshold values are those that define the minimum required criteria to meet the objectives. Qualifying values are those that enhance the value of the objectives.

4.3. Resource requirements

The role of ISRU in site selection was highlighted by [57]. As defined by the first HLS^2 workshop [69], resource objectives include containing raw materials for ISRU and civil engineering (CE) works. Both areas deal primarily with the nature of regolith (its chemistry, mineralogy, physical properties) and its handling (modification, excavation, and processing). These are shown in Table 3. Threshold values are those that define the minimum required criteria to meet the objectives. Qualifying values are those that enhance the value of the objectives.

In Situ Resource Utilisation has the potential to drastically reduce mission costs. It achieves this through reducing the mass be sent to Mars by up to 80% [2,76]. Therefore some degree of ISRU is a feature of most of the Mars mission architectures proposed in the last quarter century. Examples include the studies of [109,29-31], [115], and [8].

The most important potential resource is water, present in martian regolith at mid- to high-latitudes as ice [15] and as widespread deposits

Table 2
Science objectives for a crewed mission to Mars (modified from [69].

Discipline	Value	Objectives	
Astrobiology	**Threshold**	**And/or**	**Potential for past habitability**
			Potential for present habitability or refugia
	Qualifying	Potential for organic matter with exposure at surface	
Atmospheric science	**Threshold**	**Noachian or Hesperian rocks with trapped atmospheric gases**	
	Qualifying	Meteorological diversity in space and time	
		High likelihood of surface-atmosphere exchange	
		Amazonian subsurface or high-latitude ice or sediment	
		High likelihood of active trace gas sources	
Geoscience	**Threshold**	**Range of martian geologic time; datable surfaces**	
		Evidence of aqueous processes	
		Potential for interpreting relative ages	
	Qualifying	Igneous rocks tied to 1+ provinces or different times	
		Near-surface ice, glacial or permafrost	
		Noachian or pre-noachian bedrock units	
		Outcrops with remnant magnetization	
		Primary, secondary, and basin-forming impact deposits	
		Structural features with regional or global context	

of polyhydrated sulphates [39]. Water is the essential precursor to full propellant production and fuel cell reactants (e.g. hydrogen, methane, oxygen), and for life support as both water and a source of oxygen.

Excavation of ice and sulphates for water extraction will require the ability to handle regolith. This is also needed for CE tasks [51]. These objectives are likely to be met on the first missions to enable resources and technologies for later expeditions [1]. Later missions might investigate the use of clays and plaster of Paris (from gypsum) for construction, extraction of metals such as magnesium from sulphates, and the suitability of martian soils for food production, and other high priority investigation.

5. Previous work

The value of the overall Meridiani area as a region for exploration is shown by interest from previous unmanned missions and by other submissions to the first HLS^2 workshop. No fewer than nine sites in the region were proposed as candidates for the Mars Exploration Rover program [43]. The actual landing site of *Opportunity* [98] occurs within our proposed exploration zone, as did three other sites under consideration, two in Miyamoto crater and one not far from the selected landing site. A further six proposed sites occur less than 200 km from ours, one more in Miyamoto, two to the north and three to the east.

Four landing sites in the Meridiani region were proposed for the MSL/*Curiosity* mission [41,45], our LZ lies within the landing ellipse of one of them, site 30 of [45]. Three other sites occur within ~200 km of ours, two in Miyamoto crater and one to the southwest in the Meridiani uplands.

An ellipse northwest of the Opportunity landing site was chosen for the 2016 *Schiaparelli* lander. Studies of the conditions within the proposed ellipse were carried out by [82,83,86,93].

Lastly, three other EZs were proposed at the FLWS that overlapped with ours. One [25] was essentially identical. A second [108] somewhat to the north near the centre of Miyamoto crater. A third, targeting Firsoff Crater [81] lies further west, but overlaps with the western part of our EZ.

Consequently, with considerable literature on the region, Meridiani Planum constitutes one of the best studied areas of Mars. There is a high density of imagery collected in support of proposed landings sites and actual missions, as well as ground truth from *Opportunity*. This allows more detailed assessment of potential science targets, possible resources, and safety concerns than almost any other area of Mars, with the possible exception of Gusev and Gale Craters.

6. Location

The southern Meridiani Planum landing site is located at 5°30' 2.46"W, 3° 5' 4.84"S, and is at an elevation of −1574 m with respect to datum. It lies on the smooth plains of Meridiani, 15 km north of where the plain sediments lap onto an infilled palaeoestuary, on the edge of the Meridiani uplands (Fig. 2). The ROIs of the area are summarised and grouped in Table 4.

7. Landing zone

The immediate area surrounded the landing site, out to a radius of 15 km, we call the landing zone (LZ), as distinguished from the landing site, where hardware in landed on the surface of Mars. The LZ is shown in Fig. 8, including notional approach and ascent paths for spacecraft, suggested landing sites, possible zones for infrastructure, and ROIs for resources and science. The ROIs all line within a 15 km radius of the habitat zone, and represents the proposed walk-back distance of a pedestrian EVA [31]. The LZ would be explored during the early phases of the surface mission and would allow testing of all technologies and methodologies needed for more distant exploration.

7.1. Safety

The proposed landing site is one that was among the original candidates as a MSL/Curiosity landing site [41,45]. It therefore meets the human landing site safety requirements as defined at the HLS^2 workshop [69]. The workshop assumed the same requirements as MSL with the proviso that the crewed lander would have to have a target accuracy of 100 m diameter [69].

We argue on this basis that the LZ meets all landing requirements for a crewed mission with respect to relief, slope, roughness, and winds (Table 1). HiRISE imagery (Fig. 4) shows that the surface of the landing site closely resembles the parts of Meridiani Planum traversed by the *Opportunity* rover mission on route to Endeavour crater. Flat-lying sedimentary rocks are exposed at the surface or under a shallow patchy cover of wind ripples (Fig. 5) no more than 1 m thick [95].

Table 3
Resource (ISRU and CE) objectives for a crewed mission to Mars (modified from [69].

Discipline	Value	Objectives		Priority
Water resource	**Threshold**	**And/or**	**Potential for ice or ice/regolith mix**	1
			Potential for hydrated minerals	
		Quantity for substantial production		
		Potential to be minable by highly automated systems		
		Located <3 km from processing equipment site		
		Located no more than 3 meters below the surface		
		Accessible by automated systems		
	Qualifying	Potential for multiple sources of ice, ice/regolith mix **and** hydrated minerals		
		Distance to resource location can be >5 km		
		Route to resource location must be (plausibly) traversable		
Civil engineering	**Threshold**	**~50 sq km region of flat and stable terrain with sparse rock distribution**		1
		1–10 km length scale: <10°		
		Located within 5 km of landing site location		
		Abundant cobble sized or smaller rocks and bulk, loose regolith		
		Utilitarian terrain features		
	Qualifying	Foundation improvement & surface stabilisation (landing pads, roads, berms, etc.)		1
		Ability to build structures & enhance radiation shielding for crew (and `possibly plants)		2
Food production	Qualifying	Low latitude		1
		No local terrain feature(s) that could shadow light collection		
		Access to water		
		Access to dark, minimally altered basaltic sands		
Metal/silicon resource	**Threshold**	**Potential for metal/silicon**		2
		Potential to be minable by highly automated systems		2
		Located less than 3 km from processing equipment site		2
		Located no more than 3 meters below the surface		2
		Accessible by automated systems		2
	Qualifying	Potential for multiple sources of metals/silicon		2
		Distance to resource location can be >5 km		2
		Route to resource location must be (plausibly) traversable		2

The sedimentary rocks are known to be mechanically weak with respect to abrasion [49], however it is likely they will provide a reasonable bearing surface for vehicles, habitats, and other structures when the surface is flat. The specific grind energy (SGE) required of the rock abrasion tool on *Opportunity* for the sedimentary rocks at Meridiani was between 46.2 and 0.145 J/mm^3, with an average of 3.76 J/mm^3 [49]. This compares to terrestrial limestones and shales with SPEs of 17–21 and 5.2 J/mm^3, respectively [5]. Substrate erosion by the supersonic exhaust of landing rockets has been considered a major potential hazard by [74]. However, it is likely to be significantly better than the unconsolidated regolith described by those authors.

The aeolian and residual cover at the *Opportunity* site was measured by interaction between *Opportunity* components and the regolith of Meridiani Planum [5]. These data showed the Opportunity landing site at Eagle crater has an undisturbed bearing strength of ~80 kPa with ~5 kPa of cohesive strength and an angle of internal friction of ~20°. Other soil engineering properties were derived from wheel trenches and wheel scuffs [101]. These measurements yielded friction angles of 30–34°. Cohesions in trenches were measured by two methods. Ratios of electromechanical work by the wheel motors gave cohesion values of 0–4.5 kPa, while those derived from modelling shear stress along the portion of the wheel in contact with regolith were 0.6–1.2 kPa. This method also yielded median normal stress data with value of 3.3–4.8 kPa. Cohesion of regolith exposed by wheel-scuffs was measured at between 0.3 and 11 kPa.

The surface of Meridiani Planum has proved adequate for much of the *Opportunity* traverse, the shallow and patchy nature of the aeolian cover means that larger and heavier vehicles are unlikely to be bogged even though the mission of the smaller and lighter *Opportunity* rover encountered difficulties in several places. Data from the *Opportunity* mission shows that dust is only a minor component of the regolith of Meridiani Planum [95]. This confirms the regional thermal inertia mapping using the methodology of [58] in Fig. 6 that showed little or no dust in the area of the *Opportunity* traverse or across the rest of the EZ. Class 1 (blue) thermophysical materials were directly sampled by Opportunity in Meridiani, and found to be comprised of: basaltic sand and grey spherical haematite grains millimetres in diameter [20]; [35]; with sparse occurrences of rocks (400–1100 *tiu* from mini-TES) and duricrust [42,72]. These observations are consistent with the description of class 1 materials in Fig. 6 [58].

More detailed thermophysical mapping (Fig. 7) using THEMIS nighttime infrared band 9 calibrated radiance values (W cm-2 sr-1 µm), centred at 12.57 µm, were processed into nighttime temperatures (K) using the THEMIS processing web interface (THMPROC). The absolute accuracy of the nighttime temperature data is estimated to be on the order of ~4 K [35]. Nighttime surface temperatures that are calculated as the effects of variations in albedo and topography, which can result in different surfaces having different temperatures at any given time, are reduced at night [63]. Night time brightness temperature data are dominated by grain size and degree of induration, with differences in temperature primarily attributed to variations in the thermal inertia of the surface materials [19,35,62,80]. In Fig. 7, high temperature surfaces correspond to a relatively higher thermal inertia, consistent with exposed bedrock, higher rock abundance, indurated surfaces, and/or coarse particle sizes [88]. These materials occur around the crater rims (consistent with uplifted blocky material and potential exposed bedrock), Endeavour and Iazu ejecta, and in the floor of Endeavour crater (potential impact related melt unit, blocky rim derived materials, etc.). Lower temperatures indicate lower thermal inertia materials, corresponding to surfaces with higher dust coverage, finer particle sizes, and/or unconsolidated grains. These materials occur in the plains between crater units.

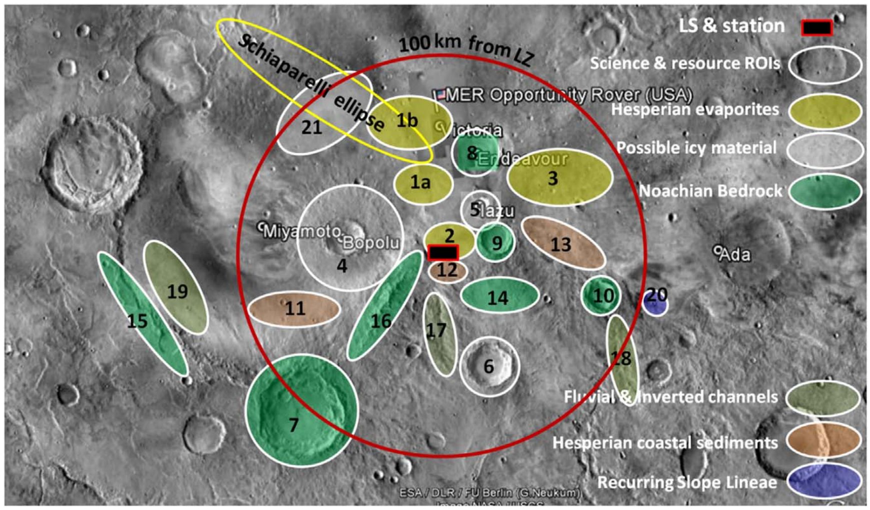

Fig. 2. Characteristics of crewed mission exploration zones on the surface of Mars. Southern Meridiani Planum area shown. Google Earth image based on THEMIS daytime infra red. Image width 420 km. See Table 4 for summary of ROI.

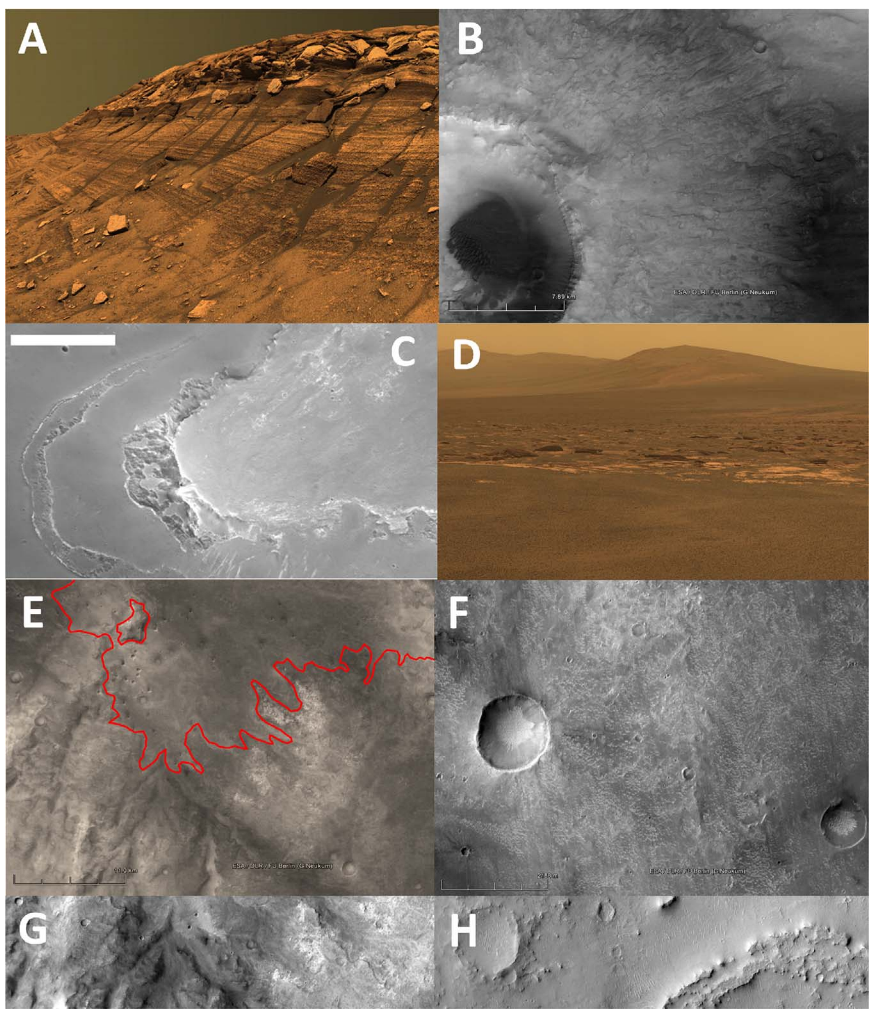

Fig. 3. Representative features of the different regions of interest in Table 4. North to top unless otherwise stated. A) Meridiani Planum evaporite sediments (ROIs 1–3), *Opportunity* rover image of exposure in Endurance crater. B) Rampart craters (ROIs 4, 6), Flow features of the Bopolu crater rampart, Google Earth image using HiRISE CTX image as base, north to right C) Edge of Iazu crater pedestal (ROI 5), HiRISE image PSP_007849_1775, scale bar 500 m, north to right. D) Uplifted Noachian bedrock crater rims (ROIs 4–10, 15–16), *Opportunity* rover image of rim of Endeavour crater, note dark-coloured sand ripples E) Coastal Meridiani Planum sediments (ROIs 11–13), HRSC image in Google Earth with palaeo-shoreline marked in red. F) Clay altered Noachian bedrock of Meridiani uplands (14), note hints of coherent bedrock structure and stratigraphy, light coloured dunes in medium-sized craters, and small fresh crater in SW corner. Google Earth image using HiRISE CTX image as base. G) Incised valleys (17–18), south of landing site. HRSC image in Google Earth. H) Inverted channel in Miyamoto crater with marginal induration (19), HiRISE image PSP_009985_1770, scale bar 500 m I).(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

Table 4
Summary table of ROIs shown in Fig. 2 and their characteristics with respect to science and potential resources (SRU and CE) objectives. ROIs with similar characteristics are grouped. Examples of these features are shown in Fig. 3.

ROI	Name	Science features	Resource features	ROI groups
1	W Meridiani Planum	Hesperian evaporites, Schiaparelli and Opportunity lander	WATER (polyhydrated sulphates), regolith materials, metals	Group 1
2	Central Meridiani Planum	Hesperian evaporites	WATER (polyhydrated sulphates), regolith materials, metals	
3	E Meridiani Planum	Hesperian evaporites	WATER (polyhydrated sulphates), regolith materials, metals	
4	Bopolu crater (rampart)	Noachian bedrock	WATER (possible ice?), metals, regolith materials	Group 2
5	Iazu crater (pedestal)	Noachian bedrock, possible former ice-rich ejecta, astrobiology	WATER (possible ice?), metals, regolith materials	Group 3
6	S crater (rampart)	Noachian bedrock, possible former ice-rich ejecta, astrobiology	Metals, clays, regolith materials, possible ice	Group 4
7	SW crater	Noachian bedrock, astrobiology	Metals, clays, regolith materials	
8	Endeavour crater	Noachian bedrock, astrobiology, Opportunity rover	Metals, clays, regolith materials	
9	Central crater	Noachian bedrock, astrobiology	Metals, clays, regolith materials	
10	E crater	Noachian bedrock, astrobiology	Metals, clays, regolith materials	
11	Coastal Meridiani Planum W	Hesperian sediments closer to possible basin shoreline	Regolith materials	Group 5
12	Coastal Meridiani Planum central	Hesperian sediments closer to possible basin shoreline	Regolith materials	
13	Coastal Meridiani Planum E	Hesperian sediments closer to possible basin shoreline	Regolith materials	
14	Clay altered hills	Clay alteration, Noachian bedrock, astrobiology	Regolith materials	Group 6
15	W Miyamoto crater rim	Noachian bedrock, astrobiology	Metals, clays, regolith materials	Group 7
16	E Miyamoto crater rim	Noachian bedrock, astrobiology	Metals, clays, regolith materials	
17	W incised valley	Incised valley in Noachian bedrock	Regolith materials	Group 8
18	E incised valley	Incised dendritic valley in Noachian bedrock	Regolith materials	
19	Inverted channels	Inverted Hesperian channels over Noachian bedrock	Regolith materials	Group 9

The proposed Meridiani Planum landing site is shown in Fig. 8. Nominal approach path from a 3° inclined orbit is shown from the WNW. Visual references for piloted landing are provided by a small hill 150 m high directly under the flight path and 12 km short of the landing site, a larger 300 m high hill to the south of the approach path, and an unnamed 15 km wide crater 20 km to the east of the landing site. Hardware, including beacons, previously landed by unmanned missions, should also be visible to guide the final landing, if required. A nominal ascent path is shown to be in an ENE direction, avoiding the HZ potentially hazardous infrastructure, or solar arrays.

Likewise, electronic navigation aids will almost certainly be available to assist surface navigation. These will be helpful given that the terrain at the LS is extremely flat with the horizon only about 3 km distant to a standing astronaut. However, as shown by Fig. 9, the

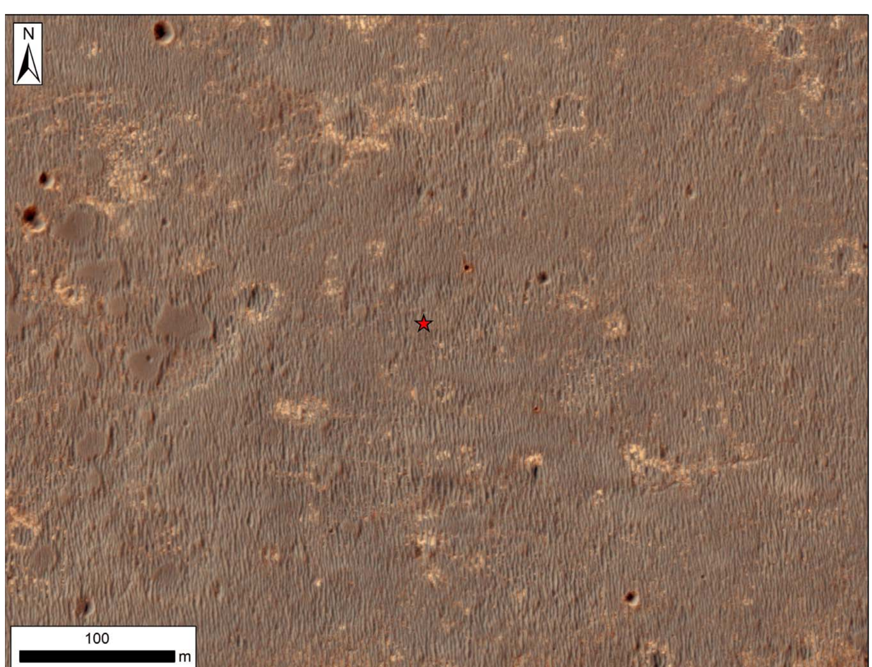

Fig. 4. HiRISE image of landing site showing patchy aeolian ripples with areas of light-coloured sedimentary bed rock showing through. HiRISE image PSP_009563_170_MRGB. Possible landing site indicated by star.

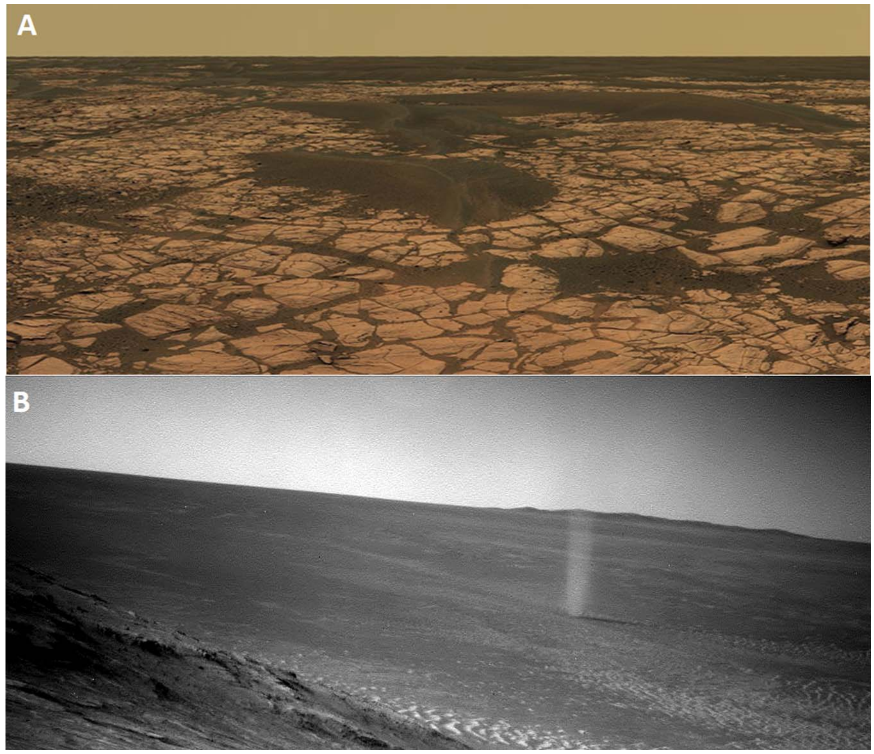

Fig. 5. A) Surface image Meridiani Planum captured by the *Opportunity* rover mission of similar appearance to proposed landing site showing small dark haematite and basalt Aeolian ripples dunes forming a patchy cover over fractured sedimentary bedrock. Sand ripple height ~30 cm, camera height 1.5 m, horizon ~3 km distant. NASA image. B) Dust devil on the floor of Endeavour crater imaged by the *Opportunity* mission. NASA image.

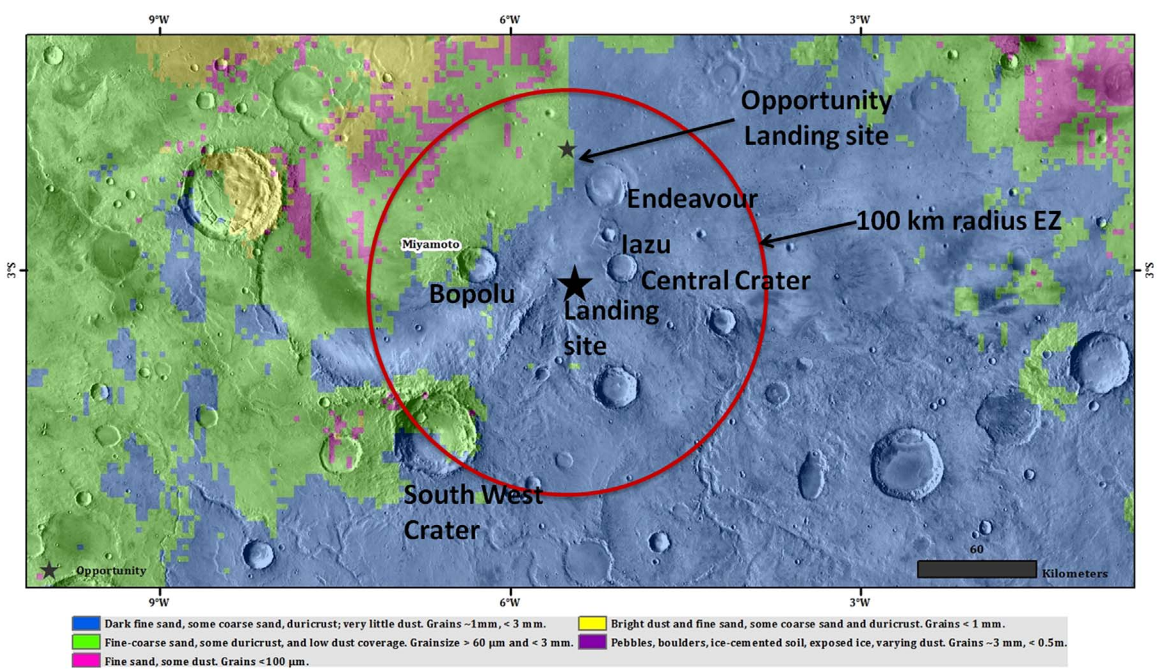

Fig. 6. Thermophysical surface material classification from TES thermal inertia and albedo mapping [58]. The EZ is dominated by low albedo fine to coarse sand typically ~60 µm-1 mm grainsize (up to ~3 mm), with sparse occurrence of bright dust in the NW portion, and some duricrust.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

rippled sand cover preserves rover tracks very well, and will be an essential guide to astronaut navigation.

7.2. Infrastructure siting

Potential locations for mission infrastructure are shown in Fig. 8. The first landing site is circled in red (1 km radius to allow for landing rocket blast). There is ample space for subsequent landing sites, black circles indicate possible landing sites for a further five missions. Further landings could be carried out at greater distances to the north, and west. Additional sites to the east are also possible, providing that they do not interfere with possible resource utilisation infrastructure (see below).

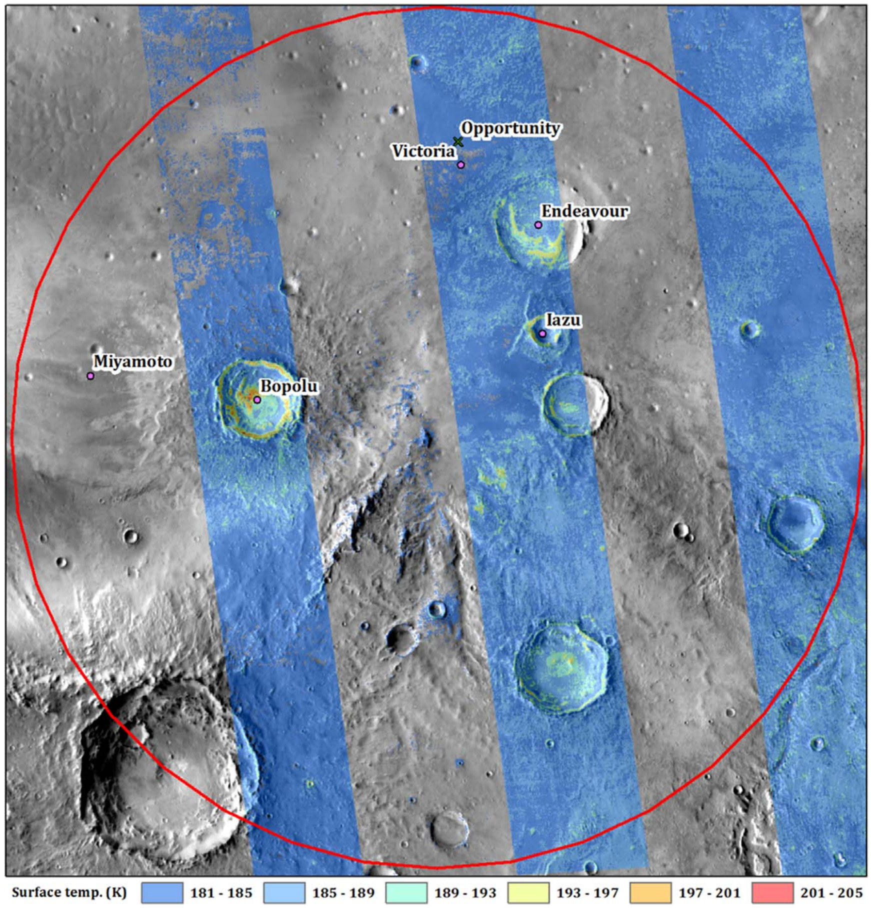

Fig. 7. Surface material temperatures from THEMIS night time band 9 (12.6 µm) infrared mapping across the EZ. High temperatures reflect the presence of coarse materials with higher average grainsize, higher rock abundance, or a greater degree of cementation. These materials can be observed in Endeavour and Bopolu crater interiors; Bopolu and Iazu crater rims and ejecta; and at the contact with the higher elevation terrains in the southern portion of the EZ.

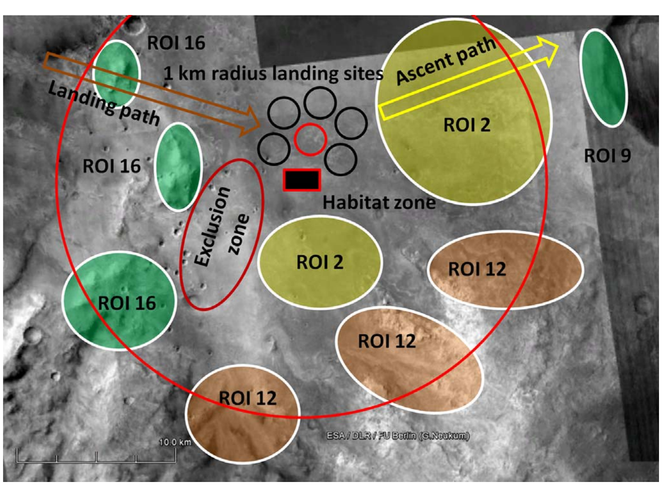

Fig. 8. Southern Meridiani LZ showing conceptual layout of features Ianding sites, exclusion zones, ROIs) in relation to ROIs. Google Earth image based on MRO CTX data. See text for explanation of features. Note that ROIs 12 and 16 in Fig. 4 have been split into multiple smaller ones in this image, due to the much larger scale. Red circle radius is 15 km. See Table 4 for further explanation of the ROIs.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

A generous habitat zone (HZ) is delineated by the red-rimmed back box in Fig. 8. The 1×2.5 km box allows ample space not only for the first landing, but extensive infrastructure associated with subsequent missions and establishment of a permanent station, if required. The HZ is at least 3 km from the closest landing site, providing a safety margin against any accidents involving fuelling operations. The HZ can be relocated further south if greater separation is desired.

The dark red ellipse in the exclusion zone is for potentially hazardous infrastructure such as reactors and is centred approximately 5 km from the habitat site. This is deemed an adequate margin by [69], though further protection against these can be provided by locating them in some of the small (100–250 m) shallow craters in the exclusion zone. We expect these craters on the ground to resemble Endurance crater encountered early on in the *Opportunity* rover mission (Fig. 10). Alternatively this area at least 5 km from the HZ and 3 km from the nearest potential LS, could be used for solar arrays because that will not be over-flown during landing and ascent and will not be regular traversed after the initial surveys.

The hills to the west of the landing site and the crater rim to the east may also be suitable sites for the deployment of wind turbines to supplement solar arrays. Wind turbines are a potentially viable energy source, operating in particular when solar arrays are ineffective, during the night or during dust storms where insolation in reduced. Hill top locations will be exposed to higher wind velocities than plain surfaces [75].

7.3. Water availability

Availability of possible resources is an essential criterion for the LZ [51]. Polyhydrated magnesium sulphates (PHMS) are widespread

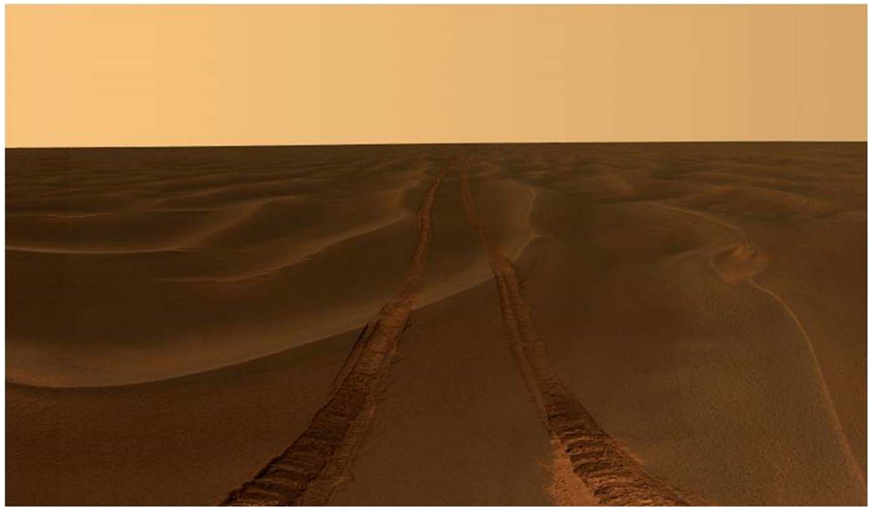

Fig. 9. Clearly visible rover *Opportunity* tracks across wind ripples on Meridiani Planum. NASA image.

across Meridiani Planum, having been observed in both orbital [36] and ground [21] data. They are known to occur in the proposed landing site [111]. This includes the areas shown as ROI 2 in Fig. 8. Although two sub-areas are shown for clarity these sediments are likely to continue right across the landing site and adjacent areas [34].

These PHMS – examples include epsomite, ($MgSO_4{\cdot}7H_2O$), kieserite ($MgSO_4{\cdot}H_2O$), hexahydrite ($Mg(SO_4){\cdot}6H_2O$), bloedite $Na2Mg(SO4)_2{\cdot}H_2O$), and meridianite ($MgSO_4{\cdot}11H_2O$) - contain 14–62% water. They comprise 10–35% of the bedrock sediments at the Opportunity landing site [20] and thus, depending on mineralogy, these sediments may yield 5–20% of their mass as water on heating. Most PHMS dehydrate at relatively low temperatures of 100–325 °C [18]. Excavation of a few tens of cubic metres of these sediments can therefore potentially supply all the water needs of a Mars mission, including that needed for propellant production [22]. Although no prototype of water extraction from sulfates has been built, the manufacture of plaster is by gypsum dehydration is a large scale and well understood industrial process, with over 83 million tonnes manufactured in 2016 [94]. Collection of evolved water would be by simple condensation [22]. Gypsum dehydration temperatures, first to hemihydrite and then to anhydrite, occurs at 80-150 and 150-250 degrees, respectively [66]. This range is broadly comparable to that shown by a range of PHMS minerals.

The flat-lying PHMS bearing sediments occur either at the surface or beneath a patchy cover of aeolian sand and lag (Fig. 5A) of no more than 1 m in thickness [95]. The resistance of these sediments to abrasion is low, with SGEs equivalent to terrestrial shales and limestones [49].

We conclude that the PHMS of the landing site are potentially a major water resource that could sustain large scale and long term human activities centred on the HZ. Given current knowledge of the surface, they could be extracted by the relatively low level heating (<

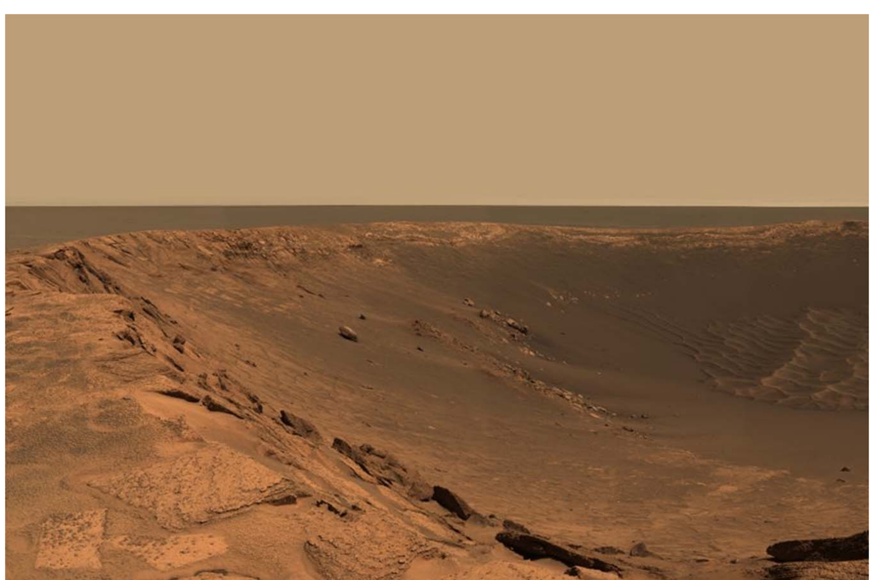

Fig. 10. Endurance crater, imaged by the *Opportunity* rover mission, is similar to a number of craters in the LZ at Meridiani Planum. NASA image.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

325 °C) of easily excavated, shallow (10 cm and potentially deeper) regolith, at a rate of less than one tonne per sol from the ROIs highlighted in Fig. 8. Unlike water extracted from ice, water extracted from PHMS is unlikely to pose a biological hazard, although any interstitial ice present within the soil may constitute a potential hazard.

7.4. Science regions of interest

Four groups of Science ROIs (2,9,12 and 16) have been identified in the immediate vicinity of the landing site (Fig. 2). Science ROIs 9 and 16 represent uplifted Noachian bedrock in the rims of Miyamoto and an unnamed 15 km diameter crater, respectively. The targets shown as ROI 12 consist of Hesperian sediments of Meridiani Planum, inferred as coastal from their context, in contact with the Noachian Meridiani uplands. The contact is complex, with Hesperian sediments filling incised valleys in the uplands, probably forming palaeoestuaries. Each of the ROI groups offers science targets in the three main discipline areas of astrobiology, atmospheric sciences and geosciences.

The evaporitic sediments of Meridiani Planum [111,21,49] that make up the group 2 sites may have been too saline to have been attractive habitats for organisms [104,64,96] but have high preservation potential for microfossils, organic matter and isotopic signatures, if present. Exotic organic matter and microfossils could have been transported to these sediments from elsewhere, either by wind or the palaeovalleys draining the Meridiani uplands. Uplifted crater rims (ROI groups 9 and 16) may have been sites of long-lasting hydrothermal systems, as observed at Endeavour Crater further to the north [79,97]. Such impact-generated hydrothermal systems have been identified as potential habitats for thermophilic organisms, by analogy with impact-generated hydrothermal systems such as those of Haughton Crater in Canada [24]. The composition of the Noachian bedrock itself, whether in the uplifted crater rims (ROIs 9 and 16) or Meridiani uplands (ROI 12) is not known. Clays are present in ROI 12 (Sullivan et al., 2012) but whether this is due to hydrothermal alteration, sedimentary deposition, or weathering, is not known. If sediments are present then the Noachian bedrock may well contain astrobiological targets. This is likely to be determinable only by visits to outcrops by astronauts. No currently habitable environments are presently known in the landing site area.

The overall low relief, smooth surfaces, gentle slopes, and general accessibility of Meridiani Planum EZ will support a range of climate and atmospheric sciences. These features will facilitate opportunities for all sky observations and sounding by balloons. Studies of local and topography induced weather phenomena are not well supported by the EZ, except perhaps locally adjacent to steeper hills and younger craters. Dust devils have been observed by the Opportunity rover mission [106] and can be studied by the crew (Fig. 5B). The size and accessibility of the EZ allows probing the atmosphere at certain mesoscale distances and deployment of automated instrument stations.

The two major geological boundaries between the Hesperian sediments of the plains and the Noachian bedrock of the uplands with have different radiative properties and will provide contrasting responses to insolation and development of micro meteorological phenomena. Surface-atmosphere interaction, both physical (entrainment and deposition of dust, movement of sand grains [38], deposition and sublimation of frost [67]) and chemical [70], can also be studied. These research objectives for the LZ are not linked to specific scientific regions of interest and apply across the entire EZ, rather being to specific SROIs.

Palaeoclimate studies will be enabled by the record of Noachian and Hesperian aqueous alteration and processes [111], [54] in both the Meridiani uplands and plains. Atmospheric gases ranging in age from Noachian through to Amazonian may be trapped as impact glass inclusions, with the rim of Miyamoto Crater, being probably the oldest and certainly the largest impact event in the EZ, the most likely location for discovery. Fluid inclusions in veins, such as those associated with Endeavour Crater to the north [97] and evaporites of the Burns Formation [47] will provide data on fluid compositions, trapping temperatures, and trapping pressures, thus also assisting reconstructing palaeoenvironmental history and palaeoclimate.

The proximity of the landing site to the contact between the Noachian Meridiani uplands and the Hesperian sediments of Meridiani Planum allows many of the geosciences objectives to be met. ROI 2 represents the flat lying Hesperian evaporitic sediments of Meridiani Planum. ROI 9 and 16 represent uplifted Noachian bedrock in the rims of Miyamoto and an unnamed 15 km diameter crater, respectively. ROI 12 is made up of exposures of Noachian bedrock. These exposures and their dissected surface will provide datable rocks and surfaces that will allow decipherment of the history of the subsequent Noachian landscape evolution. Satellite data shows that these rocks have experienced a history of aqueous alteration and clay formation [111], although the protolith is not understood. These Noachian rocks have been dissected by Late Noachian or Early Hesperian drainage [54]. The contact relations with the overlying sediments of Meridiani Planum have undergone preliminary investigations at Endeavour Crater via the *Opportunity* rover mission [97], many more opportunities are afforded by infilled palaeodrainages of ROI12 and the onlapping relations to the upraised rim of Miyamoto Crater (ROI16). Small scale features of the Meridiani Planum succession similar to those observed by the *Opportunity* rover mission [47] are also likely to be present, and correlatable over a large area [34]. Aeolian features are likely to be minor, but small ripples and aeolian etching of rock surfaces is likely, again by analogy to features captured by *Opportunity* [102].

7.5. Other resources

The surficial sands of Meridiani Planum occur across the landing site and not just within the nominal ROI 2. They consist of wind rippled aeolian sediments (Figs. 5, 9) no more than 1 m thick [95], [102]. Ripple spacing varies from continuous to sparse, with wavelengths ranging up to 2 m and heights mostly 1–10 cm [102], though they can reach 30 cm in areas of more extensive sand cover [99]. Grains, as described by [95], are mostly 40–150 µm (very fine to fine sand) with minor silt (< 50 µm) and coarse grains (0.6–6 mm). They are a mix of ~70% basalt derived grains, ~20% haematite concretions and ~10% sulphate minerals. The basaltic grains consist of glass, plagioclase, olivine and pyroxene and, as no basalt source rocks are known from the region, the grains are presumably transported by wind over hundreds or thousands of km from Amazonian volcanoes. The haematite concretions are derived from the bedrock [91] and make up most of the coarser grains [20]. The sulphate minerals, presumably fragments from the sedimentary substrate [91], make up only a small fraction as they are easily abraded.

Surficial deposits provide three different classes of resources; sand and gravel, basalt, and haematite. Sand and gravel scooped from the surface could be used for filling sand bags or burying equipment for radiation protection [100], being easily excavated and processed [33]. Sorted sand is of itself too fine to be suitable for road base or similar purposes [7], if coarser sands were required sieving would be needed, with the proportion of medium to coarse sand and gravel appear low, ~20% of the total [95].

Coarser regolith (cobble and boulder size) might also be suitable for road base and other forms of fill [51]. These materials may be obtained from the fractured surface bedrock (Fig. 5), especially in the vicinity of impact craters (Fig. 10).

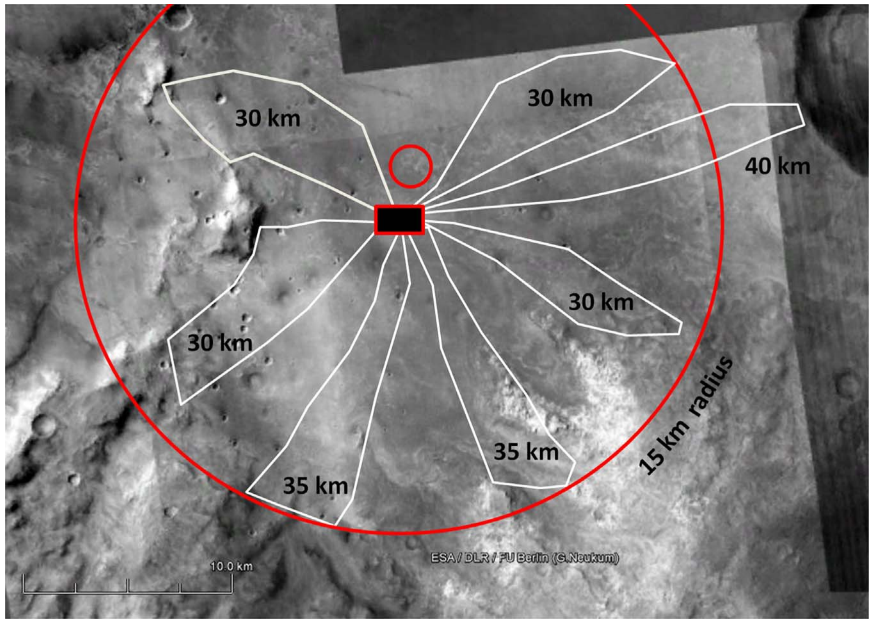

Fig. 11. Conceptual traverses in the LZ from a centrally located habitat, out to a maximum radius of 15 km. This is the proposed emergency walk-back limit [30].

The sand can be separated into its different mineral components by density. Haematite has a density of 5.26, 75% greater than basalt (~3.0), both are of higher density than the sediments (likely to be ~2.7 or less). A rotary device known as a cyclone is widely used for density separation in the mineral processing sector and would be suitable for this purpose.

Basalt is an extremely useful material for a range of manufacturing purposes; it can be sintered and used for adaptive manufacturing. In the molten state it can be poured, cast, extruded and spun [16]. Basaltic sands are an ideal starter for applications of processed basalt, being already comminuted.

Haematite is the main mineral in many terrestrial iron ores and the haematite concretions of Meridiani Planum contain ~90% haematite [90]. Concentrates of the haematite concretions from the surficial sands would be ideal feedstock for experiments in iron reduction, though not of immediate application.

Gypsum is present as a minor component of the Meridiani Planum sediments [36]. It also occurs as vein fills on the rim of Endeavour Crater [97]. Gypsum-rich beds may be found in the evaporite succession and areas of intense gypsum veining. These could be mined using the same technology as that used to mine PHMS for water. Gypsum is not only another potential water resource [1] but, the partially dehydrated waste from water extraction is the source material of Plaster of Paris. Plaster of Paris can be used for a range of structural and civil engineering processes [65], pp. 519–540, 1143–1152, [13].

The residual material after water has been extracted from the PHMS will be composed mostly of magnesium sulphate. This is comparatively rich in magnesium (20%) and potential resource for magnesium metal. However, new processes will be needed to extracted it compared to Earth, where magnesium metal is produced either from the oxide or the chloride.

High grade clay deposits consisting mostly of kaolinite and/or illite can be used for ceramic and brick manufacture. Clay alteration occurs on the rim of Endeavour Crater [28,113]. Other clays are present in the Noachian outcrops of ROI 12 [111]. Clay alteration is also likely to occur in the rim of the unnamed 15 km diameter crater east of the landing site (ROI 9) and in the rim of Miyamoto Crater (ROI 16). These clays may not, however, contain enough kaolinite required for brick or ceramic manufacture. Montmorillonite and similar smectitic clays in particular are unsuitable (e.g. [37]. Clay deposit would be investigated for their long term rather than immediate potential.

Rocks from the rim of Endeavour Crater are enriched in zinc, probably from hydrothermal activity generated by the impact that formed the 20 diameter crater [97]. Hydrothermal enrichment in other elements found in terrestrial base metal sulphide deposits are also likely, in particular copper, lead, and arsenic. It is likely that similar enrichment may be found in the rims of the unnamed eastern crater (ROI 6) and the eastern rim of Miyamoto Crater (ROI 16) which may have formed post-impact hydrothermal systems. These features too are of longer term interest for their potential significance to ISRU.

7.6. Indicative traverses

Fig. 11 shows a number of indicative exploratory traverses from the habitat zone to various regions of interest. All but one of these lie within a 15 km radius of the habitat zone, with most traverses being of 30–35 km in length and one of 40 km. These traverses are significantly longer than those carried out during the Apollo lunar missions, and are to features much further away. They extend out to the nominal 15 km “walk back” limit [30], although this would place a substantial physical demand on the astronauts. To reduce this physical demand, these traverses would be carried out by pairs of astronauts driving two unpressurised vehicles similar to the Apollo lunar rover. This way, if one vehicle was immobilised, the astronauts could return to the habitat on the other vehicle. Assuming even modest driving speeds of 13 kph, equivalent to a terrestrial cross country speed of 25 kph, a 40 km traverse would be completed in three hours, not counting stops. These traverses should be eminently achievable during the early phases of the first mission.

8. Inner exploration zone

8.1. Safety

The inner exploration zone extends out to a distance of 50 km from the landing site (Fig. 14). For clarity, ROIs exclusively within a 15 km

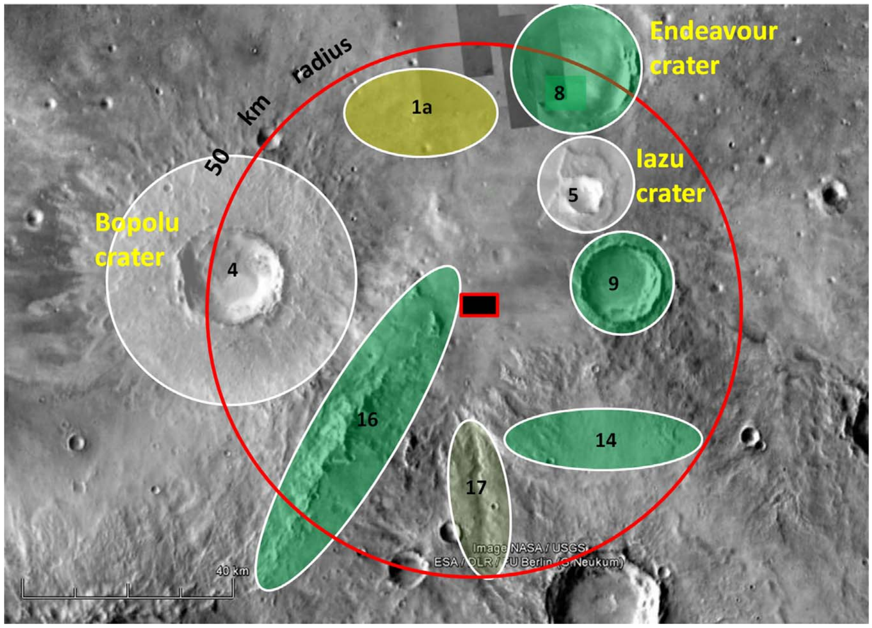

Fig. 12. ROIs and other features of the inner exploration zone. These ROIs would most likely be accessed during the middle stage of the exploratory mission. See Table 4 for explanation of ROIs.

of the landing site, covered in the previous section, are not shown. The zone consists of both the horizontal Hesperian Meridiani Planum sediment plains and the Noachian Meridiani Planum uplands. We suggest that these regions would be visited during the middle phases of the first mission.

The trafficability of the area has not been quantitatively assessed to our knowledge, or have any published results on the strength of the substrate, be it aeolian sediments, sedimentary strata or Noachian bedrock. We assume however that the aeolian cover and its sedimentary bedrock will have similar properties to those near the *Opportunity* landing site. This means that the cover has an undisturbed bearing strength of ~80 kPa, a cohesive strength of ~5 kPa, and an angle of internal friction of ~20° [5]. The sedimentary bedrock we suppose has an average SGE of 3.76 J/mm^3 [49] comparable to a terrestrial shale with a SGE of ~5.2 J/mm^3, ([5]). This assumption is consistent with the relatively few problems encountered by the Opportunity rover mission during its traverse from the landing site to the Endeavour Crater rim.

With no published data available on the Noachian bedrock exposed along the rim of Endeavour Crater (Fig. 13) we can only note that there have been no reported difficulties experienced by the *Opportunity* rover mission whilst traversing these surfaces. We will assume that these surfaces are typical of the Meridiani uplands.

In addition to electronic navigation we expect that the tracks left by vehicles crossing Meridiani Planum will be a useful visual reference for navigation (Fig. 9). Although relief is subdued, crater rims are visible for distances of many tens of km (Fig. 14). Vehicle tracks left on the uplands may not be as well developed as those on the plains but those

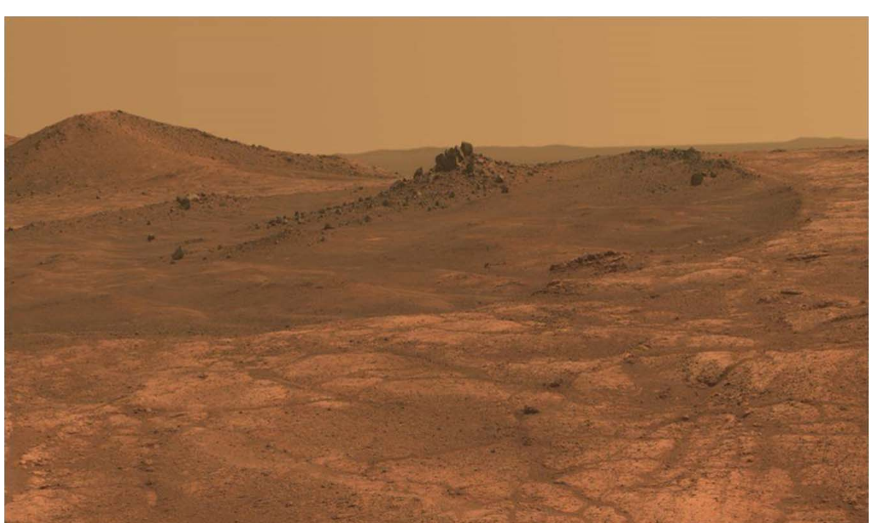

Fig. 13. *Opportunity* rover image of the terrain along the rim of Endeavour crater, Marathon valley shown. The rim is composed of uplifted Noachian bedrock, and may be typical of Noachian.

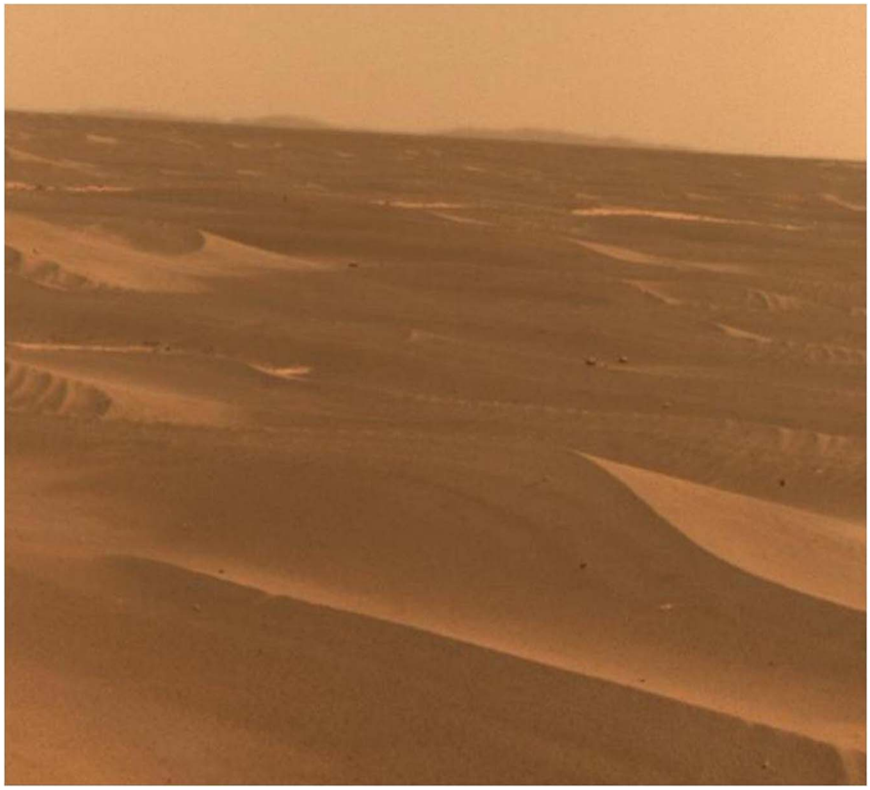

Fig. 14. View across Meridiani Planum captured by the *Opportunity* rover mission. Large wind ripples mantle the surface. The rim of Bopolu crater, ~55 km to the southwest and ~341 m higher in elevation, is visible on the horizon.

Fig. 15. *Opportunity* over image of the lower part of the Endeavour crater rim (composed of Noachian aged rocks) rising up through Hesperian sediments. Note rover tracks are visible over the Noachian bedrock, despite only a thin cover of surficial material.

of *Opportunity* on the rim of Endeavour Crater are still well developed (Fig. 15).

8.2. Water availability

ROI 1a refers to the sulphate-rich evaporitic sediments of Meridiani Planum. Its extent is indicative only as these sediments are likely to be continuous across the whole of Meridiani Planum within the exploration zone.

All water requirements of the Mars station subsequent to the first mission will likely be met close to the habitat zone. Modelling by [1] indicate that the maximum likely radius is 3 k. If more remote water sources are required, for example to resupply traverses or support field

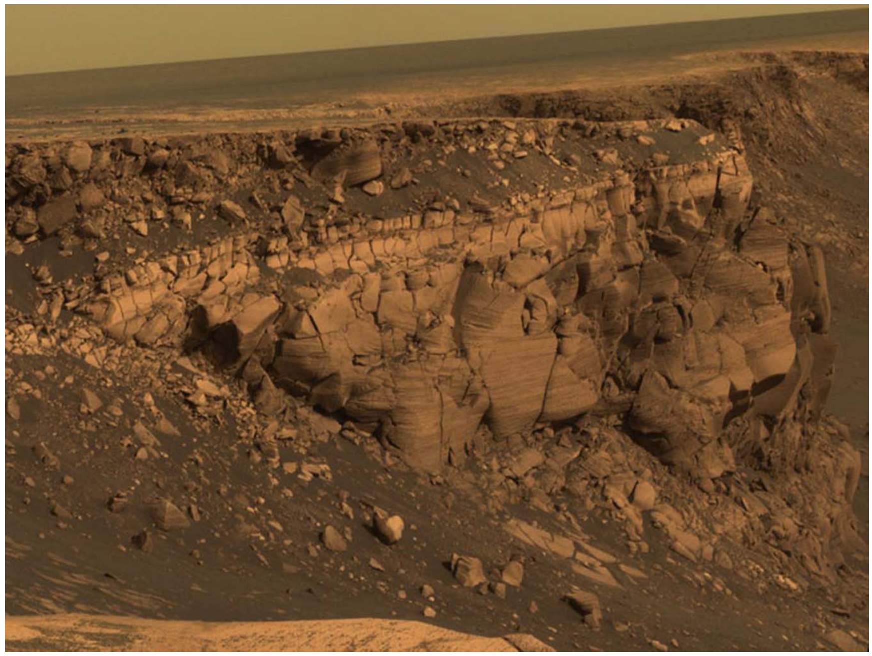

Fig. 16. *Opportunity* rover mission image of the rim of Victoria crater, ejecta blanket of Hesperian sediments with decimetre to metre-metre scale clasts, and fractured Hesperian bedrock.

camps, water may be supplied by processing of the PHMS in shallow bedrock in ROI 1a, and similar locations. This will be a long range goal, unlikely to be established in the first few missions.

The four groups of ROIs identified in the inner exploration zone (Fig. 12) consist of two crater ejecta blankets (4 and 5), three crater rims (8, 9 and 16), clay altered Noachian bedrock (14) and an incised drainage (17). Some of these targets (9 and 16) lie partly within the area covered by initial traverses from the landing site (c.f. Fig. 9).

8.3. Science regions of interest

Astrobiology targets in the inner exploration zone include the Hesperian sediments of Meridiani Planum potential hydrothermal systems associated with the impact craters, the Noachian bedrock, and both rampart and pedestal craters that may be associated with formerly icy regolith. As noted previously, the Hesperian sediments, continuations of the same unit found in the LZ, have high preservation potential for microfossils, organic matter and biogenic isotopic signatures, if present. Exotic organic matter and microfossils could have been transported to these sediments from elsewhere, although this may be less likely at the greater distance from the former shoreline. The uplifted rims of five significant craters occur in the inner exploration zone. Parts of these crater rims, the unnamed 15 km diameter east of the habitat zone and the rim of Miyamoto Crater, were accessed in part near the LZ. This more extended exploration zone allows all of the rim of the 15 km crater (9 in Fig. 12) and a 50 km length of the Miyamoto Crater rim (16 in Fig. 12 to be accessed. Three additional craters are present; Endeavour (20 km, only partly in the inner exploration zone) Bopolo (18 km) and Iazu (6 km). These rims may allow potential ancient habitats in the form of impact generated hydrothermal systems [24] to be explored. The raised ejecta blankets of Bopolu and Iazu Craters (ROIs 4 and 5, respectively in Fig. 12) both have characteristics suggestive of impacts into former icy substrates. The height of the ejecta deposits above the surrounding landscape can be used as a proxy for icy regolith thickness [60]. Bopolo resembles a pedestal crater [11], [9] with ejecta 20–60 m thick, with Iazu resembling a pedestal crater [60] with ejecta 140–200 m thick. Any ice remnants in these features are thus targets for astrobiological exploration as ice may preserve biomarkers or microbes, if present [114]. Noachian bedrock is exposed in Bopolu and other craters, with Bopolu the likely source of the shergottite-like basalt "Bounce rock" encountered early on in the Opportunity rover traverse [6].

The composition of any icy regolith preserved by the Bopolo and Iazu Crater ejecta may also provide clues to past atmospheric processes, for example deposition of equatorial ice during periods of high obliquity [68]. As in the LZ, palaeoclimate studies will be enabled by the record of Noachian and Hesperian aqueous alteration and processes (e.g. [111], [54] in the Meridiani uplands and plains. Atmospheric gases ranging in age from Noachian through to Amazonian may be trapped in impact glass inclusions of the craters, including the relatively recent Bopolu and Iazu craters. Fluid inclusions in veins associated with impact-generated hydrothermal systems may provide further insights into martian volatile history.

The proximity of the landing site to the contact between the Noachian Meridiani uplands and the Hesperian sediments of Meridiani Planum allows many of the geosciences, and some of the astrobiological objectives to be met. The contact is complex and appears to consist of many sediment-filled palaeoestuaties, with the potential for the preservation of many different depositional environments and sites for potential preservation of biomarkers and microfossils. The uplifted Noachian bedrock in the rims of the five crater rims provide exposures to Noachian crust from below the surface in both outcrop and in the ejecta. Clay alteration [111] is widespread across the Noachian uplands (ROI 14 is indicative) and may give insights into geothermal processes and perhaps weathering in the Noachian. ROI17 covers an incised drainage system with a preserved length of at least 40 km. The geomorphic evolution of this drainage system would give insights into surface processes during the Noachian to Hesperian transition [56].

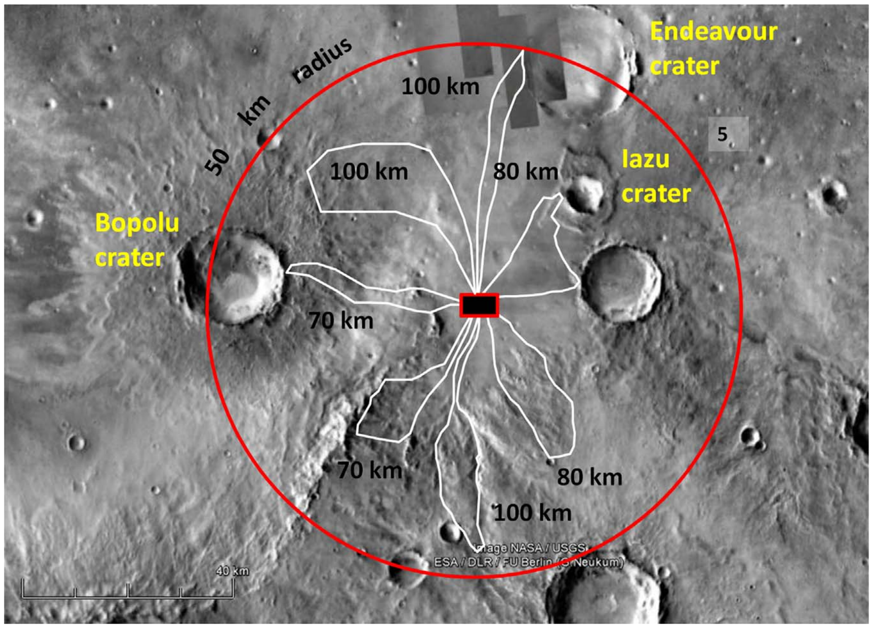

Fig. 17. Indicative traverses across the inner exploration zone. This is the maximum distance for single sol traverses by unpressurised vehicles.

8.4. Other resources

The other resources in the inner exploration zone are similar to those found near the landing site. These include surficial sands, coarser regolith associated with impact craters (e.g. Fig. 16), clay alteration and possible metallic sulphide veins associated with crater rims and Noachian uplands, and residual materials from water extraction from PHMS. With the exception of the regolith materials these are unlikely to be immediately applicable because of their distance from the LZ.

8.5. Other features of interest

The current position of the *Opportunity* rover lies at the edge of the inner exploration zone along the western rim of Endeavour crater. While the remaining life expectancy of the rover is not known, it is likely to gradually work its way further south along the crater rim. Visiting the rover and sites of its scientific observations will serve many functions. It will allow further investigations of specific features of interest with more sophisticated instruments. The state of the rover itself will be of interest to engineering researchers, concerned with the ability of spacecraft materials to withstand martian conditions. Whether any terrestrial micro-organisms have survived or even spread from the clean but not sterilised rover will be a subject for planetary protection investigations. Lastly, visiting such a historic item from the exploration of Mars will generate great public interest. Items from the rover might even be returned to Earth for preservation.

8.6. Indicative traverses

Seven indicative traverses are shown in Fig. 17. They vary in length from 70 to 100 km, which is the maximum distance that can be covered in a one sol EVAs. If carried out by astronauts travelling in two unpressurised vehicles and assuming driving speeds of 13 kph even a 100 km traverse would be completed in eight hours. This is with the

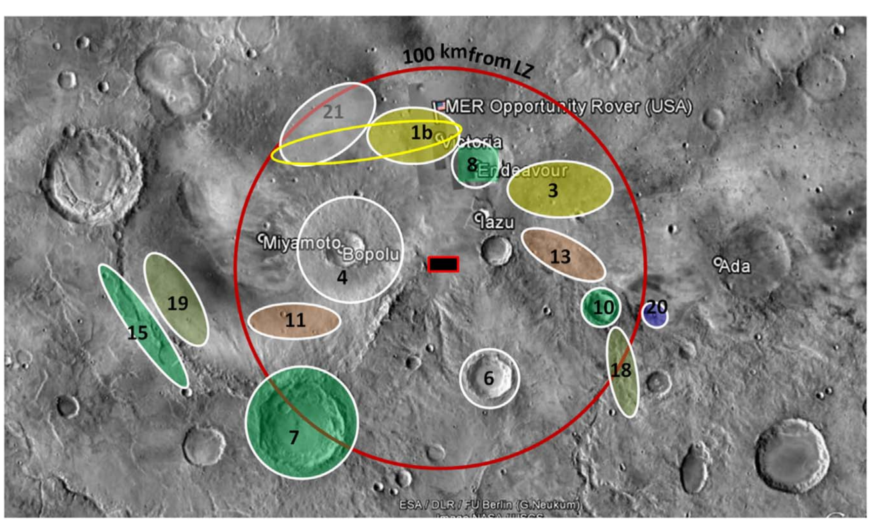

Fig. 18. ROIs and other features of the outer exploration zone. Those closer to the LZ omitted for clarity. These ROIs would be accessed during the later stage of the exploratory mission.

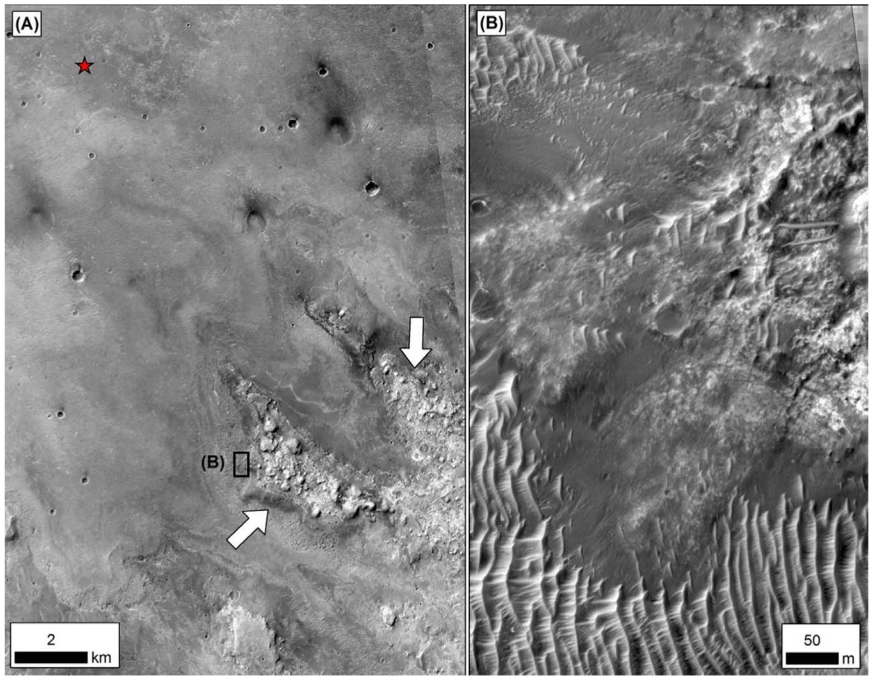

Fig. 19. (A) Examples of rocky outcrops (arrowed) located on edge of Noachian uplands south of the LZ, in HiRISE image P14_006702_1767_XI_03S005W.jp2. (B) close up of outcrop on box in (A), from HiRISE image PSP_009563_1770_MRG.

capability of a single sol's EVA, assuming astronaut consumables were supplied on the vehicles. Use of pressurised vehicles would offer additional safety margins. The traverses visit all seven ROIs in Fig. 12, providing access to all crater rims, the incised drainage system, Meridiani Planum sediments, probable icy ejecta from Iazu and Bopolo craters, and the final resting place of the *Opportunity* rover, somewhere on the rim of Endeavour Crater. Such traverses should be achievable during the middle phases of the first mission. Should unexpected technical (or other) issues occur, they could be deferred until the final phase of the mission.

9. Outer exploration zone

9.1. Safety

The outer exploration zone occurs at a radius of 50–100 km from the LZ (Fig. 18). The terrain and surface materials in the zone appears similar to that encountered closer in, so probably offers no particular safety challenges beyond those of distance. The zone is beyond the distance that can be covered within a single sol of two-way traversing, and so requires pressurised vehicles that can support multi-sol activities. Additional safety margins will be provided by these vehicles operating in pairs, possibly with unpressurised vehicles used for scouting. We predict that these would be achieved during the final six months of the mission.

9.2. Water availability

ROI 1b refers to the sulphate-rich evaporitic sediments of Meridiani Planum. The traverse of the *Opportunity* rover mission [97] has shown that these sediments extend across most of this part of Meridiani Planum. The ellipse is therefore indicative only. We do not expect water to be extracted from this ROI as all water requirements of the Mars station are likely to be met close to the habitat zone. However, as for the inner exploration zone, water supply of long range traverses or field camps may be supported by processing of the PHMS in shallow bedrock in this ROI, thus potentially extending traverse extent and duration.

9.3. Science regions of interest

Science ROIs in the outer exploration zone are shown in Fig. 18. ROI 1b consists of the evaporitic sediments that have been traversed by the *Opportunity* rover mission between landing site in Eagle Crater and Endeavour Crater. Although shown as separate, these sediments are likely to be continuous across Meridiani Planum. These sediments would pass into more proximal, shoreline equivalents to the south, closer to the contact with the Meridiani uplands (ROIs 11 and 13) and would provide insight into Hesperian surface environments. While the evaporitic environment was not habitable because of extreme salinity [104], such sediments have potential to preserve biomarkers and microfossils [64] that may have been transported from other locations.

Uplifted crater rims and ejecta (ROIs 4, 6, 7, 8 and 10) provide exposures to Noachian crust across much of the outer exploration zone, including areas that are buried beneath the younger (Hesperian) sediments. The crater rims also provide access, via outcrop and ejecta, to deeper crustal levels. In the case of the relatively young Bopolu Crater, 17 km in diameter, the crust has been excavated to a depth of 1.5 km below the rim. These exposures will be prime locations to sample stratigraphy for Noachian processes and for evidence of hydrothermal activity with relevance to trapped fluids and potential habitable niches.

The Noachian crust of the Meridiani uplands is exposed across much of the lower part of the outer exploration zone, although no specific ROIs are assigned to them. Exposures may also be found along the sides of the dendritic drainage in the far east of the exploration zone (ROI 18) which has been incised to a depth of 20–30 m. These valleys are probably relicts from a more widespread Noachian drainage system [54].

Thermal inertia data (Fig. 6) shows that dust mantling is minor to

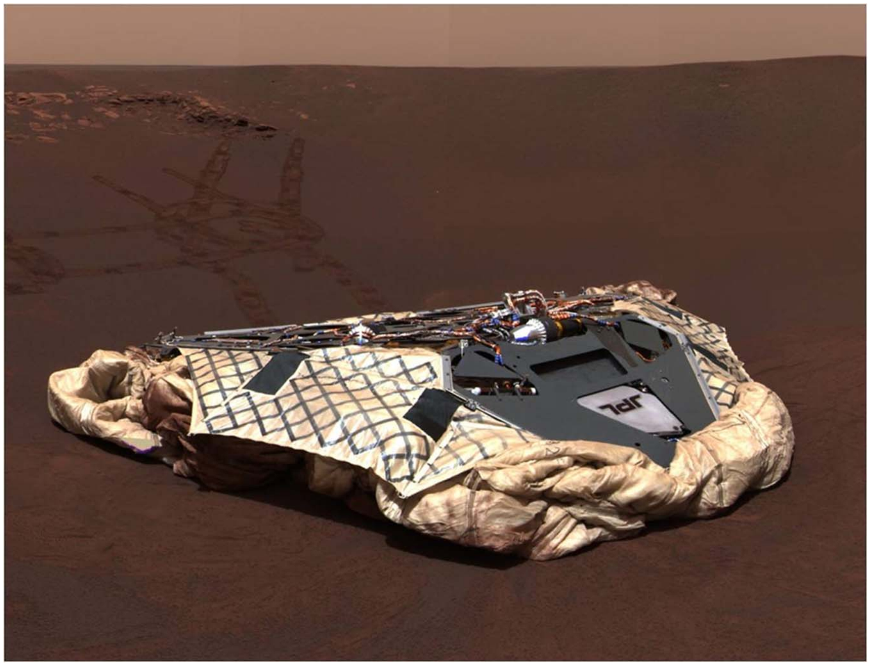

Fig. 20. *Opportunity* landing landform, some of the historic hardware in the exploration zone.

non-existent across the area of Noachian outcrop and subcrop. This is confirmed by HiRISE imagery which shows that outcrop is present (Fig. 19). Clay alteration is present [92], [3].

The ejecta patterns of two of the craters in ROI6, the relatively young Bopolu and the more degraded, unnamed crater, are of the rampart type. Rampart craters may indicate the presence of icy regolith [11,60,9]. If so, then they are potential astrobiological targets [114]. The crater in ROI6 also shows a central pit, which is a feature consistent with the former presence of subsurface ice [9,10]. Any ice associated with these features is likely to be episodic equatorial ice deposited during periods of high obliquity [68].

Several ROIs occur beyond the nominal 100 km radius [69] from the LS. These include inverted channels along the southwestern part of the floor of Miyamoto crater (ROI 19) and the southwestern Miyamoto Crater rim (ROI 15). The ease of travel of the EZ, suggested by the 42 km (to date) trek performed by the *Opportunity* mission, indicates that these features may be readily accessible, despite their distance.

The rocks of the southwestern Miyamoto Crater rim (ROI 15), a ~150 km Noachian impact may resemble those of the southeastern rim (ROI 16). It offers further exposures of uplifted Noachian rock and potential clay alteration, although the clays observed are either *in situ* or part of the overlying Hesperian succession that onlaps the Noachian [112]. The inverted channels of the southwestern part of Miyamoto Crater (ROI 19) are a striking feature of this region [71,78]. The channels that formed these drainages originally flowed northeast toward Meridiani Planum. Such inverted relief provide important clues to palaeohydrology and landscape evolution and, in our view, are well worth visiting, despite their distance from the LZ. This part of Miyamoto Crater, including ROIs 15 and 19, was also targeted for MSL/*Curiosity* [41,45] and for the MERs [43], and is therefore well documented with imagery.

Amazonian features of the northwestern part of the outer exploration zone consist of aeolian sands and residual lags. These have been mapped in some detail within the landing ellipse of the ExoMars

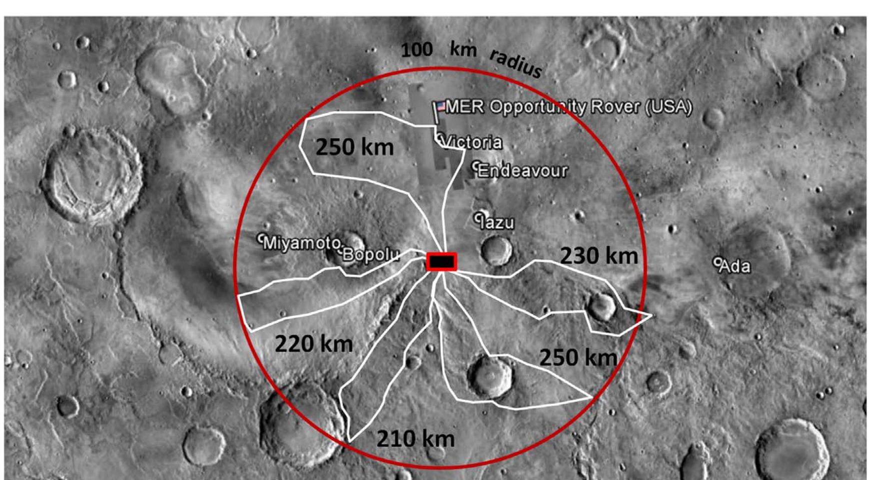

Fig. 21. Indicative traverses across the outer exploration zone. See Fig. 18 for relevant ROIs. All traverses terminate at the 100 km radius from the centre LZ, and would require multi-soil traverses with pressurised rovers to perform.

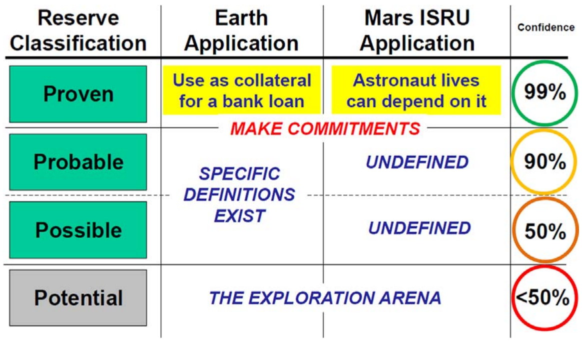

Fig. 22. Improving confidence in resource determination, terrestrial experience and martian application. Red circle = confidence likely from orbital observations, orange circle=likely confidence from unmanned surface measurements, yellow circle = confidence likely from field investigations by astronauts, green circle = confidence following mining and extraction tests. Modified from [1].(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Schiaparelli lander [93] and resemble those seen by the traverse of the *Opportunity* rover mission, which partly crossed the southeastern end of the ellipse.

9.4. Other resources

The other resources in the outer exploration zone are similar to those found near the landing site. These include surficial sands, coarser regolith associated with impact craters, clay alteration and possible metallic sulphide veins associated with crater rims and Noachian uplands. These are unlikely to be immediately applicable because of their distance from the LZ, except perhaps for some regolith materials to improve well-used tracks. The potential for future resources association on Mars will be explicated by research into geochemical signatures with such alternation.

9.5. Other features of interest

The outer exploration zone contains the remains of the *Opportunity* lander, including the landing platform, airbags, heatshield, and parachute (Fig. 20). As with the rover they carried, visiting these relics will be of interest to engineering researchers, those interested in planetary protection, and space historians. The sites visited by the rover during its journey from the landing site to Endeavour crater will also offer opportunities to follow up and validate conclusions drawn from the earlier mission. Considerable public interest can be expected, especially if any components can be returned to Earth. The region also contains the wreckage of the *Schiaparelli* lander, investigations of the debris will confirm conclusions as to the cause of failure and some components may be sufficiently intact to allow assessment of material durability under martian conditions.

Table 5
Ability of the Meridiani EZ to meet specified science goals.

Discipline	Objectives	Threshold or qualifying	Potential at Meridiani Planum
Astrobiology	Potential for past habitability	T	Yes - Including Noachian sediments (if present), hydrothermal systems associated with large impact craters, and near-shore Hesperian sediments
	Potential for present habitability or refugia	T	Possible - deep ice deposits may be present with localised brine pockets or melt zones
	Potential for organic matter with exposure at surface	Q	Yes - known Hesperian sediments, in vein of Noachian and Hesperian age, and in Noachian sediments (if present)
Atmospheric science	Noachian or Hesperian rocks with trapped atmospheric gases	T	Probably - Noachian impact glasses with trapped atmospheric gases may be associated with Miyamoto and Endeavour craters, trapped Hesperian gases with Iazu crater. Fluid inclusions in veins and evaporites may be found also contain an atmospheric component
	Meteorological diversity in space and time	Q	Yes - High trafficability facilitates placement of meteorological sensors across the EZ. Topographic variability allows investigation into small-medium scale meteorological effects, including dust devils
	High likelihood of surface-atmosphere exchange	Q	Yes - Frosts [67] and surface crusts [103] imaged by *Opportunity* point to interaction between the surface regolith and the atmosphere.
	Amazonian subsurface or high-latitude ice or sediment	Q	Possibly - Relict ice may be present at depth beneath the ramparts and pedestals of several craters (potential to be determined)
	High likelihood of active trace gas sources	Q	Unknown
Geoscience	Range of martian geologic time; datable surfaces	T	Yes - Noachian bedrock, Hesperian sediments, and Amazonian crater ejecta and Aeolian deposits are all present
	Evidence of aqueous processes	T	Yes - Abundant evaporitic sediments, incised and inverted fluvial valleys, hydrothermal veins
	Potential for interpreting relative ages	T	Yes - from stratigraphic relationships and numerical dating of rocks and exposure surfaces, allowing determination of formation ages and denudation rates
	Igneous rocks tied to 1+ provinces or different times	Q	Unknown – But Noachian bedrock and surface sands likely to contain volcanic rocks of different ages
	Near-surface ice, glacial or permafrost	Q	Possibly - Relict ice may be present at depth beneath the ramparts and pedestals of several craters (potential to be determined)
	Noachian or pre-noachian bedrock units	Q	YES
	Outcrops with remnant magnetization	Q	Probably – LIkely to be present in igneous rocks, hydrothermal alteration, and sediments
	Primary, secondary, and basin-forming impact deposits	Q	Partly present - Both primary and secondary impacts known, the site is distal to basin forming structures
	Structural features with regional or global context	Q	Unknown
	Diversity of aeolian sediments and/or landforms	Q	YeS - Both large and dark aeolian deposits at scales from ripples to small dunes. Range of ventifacts included etched surfaces and dedos [103]

9.6. Indicative traverses

Five indicative traverses are shown in Fig. 21. These extend out to the 100 km radius and approximate traverse distances are 210–250 km. These could be covered by one and two sols of driving by pressurised vehicles, with additional time required for investigation of sites of interest. These five traverses would explore all of the ROIs within the outer exploration zone and revisit some features in the inner zone. We expect these to be visited in the final phase of the first mission, although, should there be unexpected issues, be they technical or scientific, they could be deferred until subsequent missions.

10. Discussion

10.1. Safety

The landing site meets specified landing safety criteria with respect to wind, slope, and roughness, as defined by the MSL-based selection criteria [41,45]. These factors extend over the entire MSL landing ellipse (20×25 km), which is approximately equivalent to our inner exploration zone.

Additional safety factors within our exploration zone are the scarcity of steep slopes, thick dust, or major sand deposits. Consequently there are few constraints to surface movement across the EZ except for the steepest crater walls. Furthermore, these characteristics extend well beyond the nominal 100 km radius of the EZ, opening the possibility for much longer range traverses by subsequent missions. The low relief allows low hills and crater rims to be visible across tens of km, facilitating navigation. Combined with the visibility of vehicle tracks this enables emergency navigation even in the event of the failure of all aids. We argue that the low relief sites will provide matching science to other, more spectacular high relief sites on Mars, but will be much safer to access.

Lastly, the longevity of the *Opportunity* rover (over 12 years at the time of writing) shows that the Meridiani environment is not excessively harsh on spacecraft systems. Although the traverse distance of *Opportunity* (over 42 km at time of writing) is small compared to what would be covered by a crewed mission, the success of the traverse, with only two bogging incidents in sand ripples that would be unlikely to cause problems for larger crewed vehicles, indicates that trafficability hazards are low.

10.2. Water resources

Resource delineation on Earth proceeds through a formally defined process [59] from possible to proven, with increasing levels of confidence at each stage (Fig. 22) as discussed by [1]. These correspond to increasingly detailed and focussed investigations, from remote sensing to preliminary field investigations (perhaps equivalent to surveys by unmanned rovers on Mars), to more detailed field investigations (equivalent to astronaut studies), to final confidence (pilot plant testing of mining and resource extraction technologies and verification of water quality). The last two steps would be the goal of the first crewed mission, although, should the last step prove difficult, it could be extended over two missions, with the first defining probable resources and the second demonstrating proven resources.

We emphasise that of the five sites visited by surface missions to date on Mars that lie within 50 degrees of the equator, Meridiani is the only one with resources in the possible category. With enough ground truth to define possible water resources, resource delineation at Meridiani is already a step ahead of all other LZs proposed in [69] for which only orbital data ie. indicating only potential resources, exist.

The amounts of water required are small as far as resource extraction projects go. [31] indicated that daily crew water use on the Mars reference missions (Addendum version 5) was 4.2 L per person and would be recycled at an efficiency of 85%. The shortfall would be made up from wet food storage. A surface reserve of 539L was indicated for contingencies, namely 30 sols of open-loop requirements at reduced consumption allowing time for repair. This amount is relatively small, about 6% of indicated consumable requirements. With validation of actual water extraction rates, efficiencies, and power requirements on the first mission, later missions could rely on local water resources for consumption and for production of methane propellant. A total of 16 t (16,000 L) of water from martian resources would provide the requirements for propellant production and life support [1]. Given water contents of the Burns formation at Meridiani of the order of 5–20% water, between 80 and 320 t would need to be excavated, with a volume of between 30 and 120 m^3 assuming a density of 2.7.

It would be unwise to rely on the uncertainties of the regolith extraction processes to supply such a mission critical item as water on the first mission unless proved and stockpiled before the crew departs Earth. A goal of the first mission should be to establish resources at a high confidence level (such as in the proven category of [59]. This is consistent with the recommendations of [1].

The lateral extent of the sulphate-bearing sediments of the Meridiani plains throughout much of the EZ means that potential water supplies exist at significant distance from the landing site. These could be used if required to replenish long range traverses, supply outstations, or support relocation of the main station.

10.3. Science regions of interest

The diversity of science ROIs and their accessibility across the EZ means that most of the defined science objectives shown in Table 2 and defined by [73] and in [69] can potentially be met. These are summarised in Table 5, where out of six Threshold criteria, four are met, one is probably met, and one possibly met. Of the 12 Qualifying criteria, five are met, one is probably met, one possibly met, and one partially met, four are unknown.

10.4. Other resources

Four primary objectives for ISRU and CE for all EZs on Mars were recognised in [69]. The most immediate resources apart from water that might be utilised are the aeolian sands, which may be used to construct berms and cover infrastructure. Coarser deposits occur in the shallow subsurface and in ejecta of smaller craters. These could be used from the first landing onwards.

The sands also contain basalt and haematite grains that may be utilised for fabrication of basic structures at a later date [33]. We do not expect this during the first few missions, but we do expect research into their utilisation. The same is true for using residual hemihydrates from water extraction from gypsum [1] to manufacture plaster of Paris. Later missions might investigate the use of clays [100] and plaster of Paris for construction, extraction of magnesium from sulphates, and the use of martian soils for food production [100].

All these materials occur across the Meridiani plains and their lateral extent means that they could be used in establishing outstations or relocation of the main station, if required. Regolith resources of the Noachian uplands are not known, however, evaluation of eroded landscapes along the rim of Endeavour crater [44] allows us to infer the widespread presence of aeolian sand and also coarser regolith materials.

The presence of zinc enrichment in veins associated with the rim of Endeavour crater suggests that hydrothermal deposition of chalcophile

Fig. 23. View across Endeavour (NASA image, processed by James Sorenson).

and other elements may occur post impact. While their resource potential is unknown, location of such features and their documentation will form part of the science and research objectives of the first missions.

10.5. Historic hardware

Meridiani Planum contains a wide range of historic space hardware associated with the *Opportunity* mission [98]. The hardware includes the rover itself, the landing platform and associated airbags (Fig. 20), the backshell, landing rockets, parachute, and heatshield. Debris from teunsuccessful *Schiaparelli* lander also occurs in the area.

Both missions have generated an extensive amount of orbital imagery in support of their site selection and on-going operations. *Opportunity* has provided ground truth with respect to bearing strength and trafficability available in only a handful of areas on Mars. The ability to follow up of historic observations by *Opportunity* with the much more diverse and capable suite of instruments carried by the crewed mission will add to the value of the historic data, as will comparison of any changes in the landscape, for example with respect to dunes and ripples, that have occurred in the 20–30 years since the original observations.

As well as being of public and cultural interest, studying these objects will be of scientific and engineering importance. Their condition after 20–30 years of exposure to the martian environment will inform choice of materials and systems for future missions. This would be analogous to the retrieval of items from the *Surveyor 3* lander by the Apollo 12 astronauts after resting for three years on the lunar surface [61], or studying the effects of the low Earth orbit environment on materials carried by the Long Duration Exposure Facility (LDEF) for almost six years (e.g. [46].

The *Opportunity* rover was not designed to search for life, so they are classed as category IVa missions [26]. This means that they have been built to have a biological burden no greater than Viking lander pre-sterilization levels, i.e. clean but not sterile. After 20–30 years on the martian surface, the survival of any spores on the surface or interior of the spacecraft will be of considerable interest to astrobiologists, as will testing to see if any have spread beyond them and actually colonised the martian surface. Again, comparison with biological studies of the *Surveyor 3* lander [40] and the LDEF satellite [52] illustrates potential investigations.

10.6. Public engagement

The first crewed landing on Mars will generate public interest of a scale not seen since Apollo 11. While some concerns have been expressed that the low relief of the Meridiani EZ compared to other sites proposed at the first HLS[2] workshop (e.g. Gale Crater or Noctis Labyrinthus) will be disappointing to the public (M. Anderson pers. comm. 2016), the vistas across large craters and plains (e.g. Fig. 23)

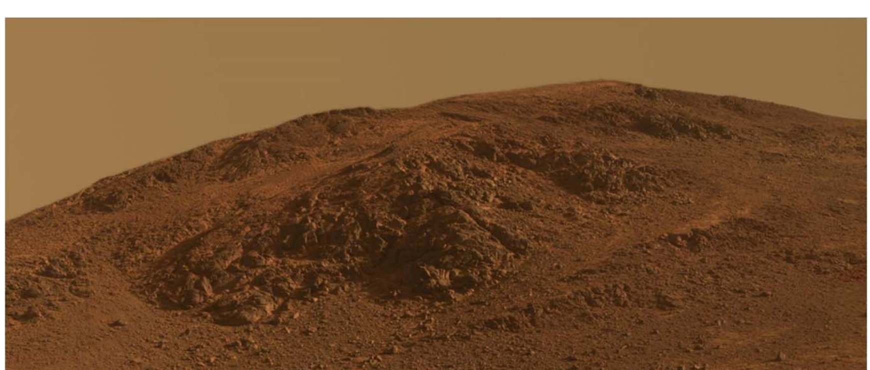

Fig. 24. Knudsen ridge showing outcropping altered Noachian bedrock on the rim of Endeavour crater (NASA).

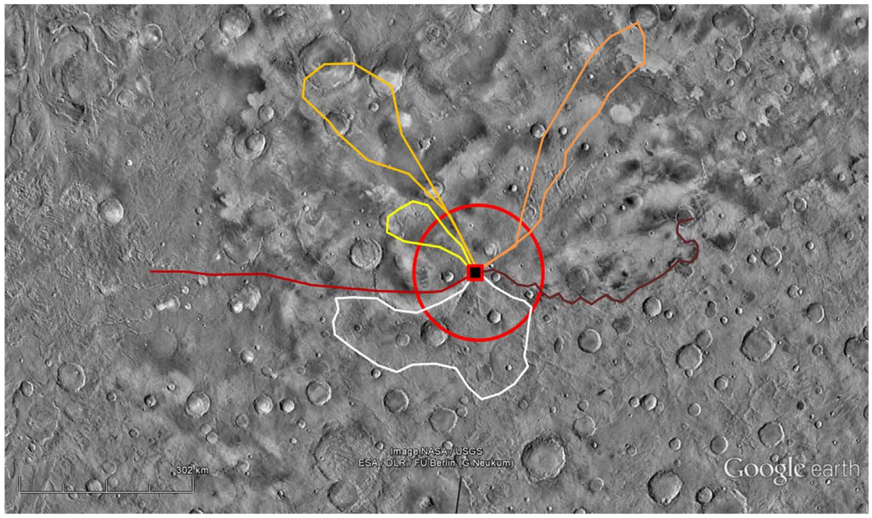

Fig. 25. Conceptual long range traverses beyond the nominal 100 km radius Meridiani EZ (red circle). Traverses visit incised reticulated drainage of southern Noachian uplands (white line), Iani Chaos (dark red line), ROIs proposed in the EZ of [108] (yellow line), Firsoff crater area [81] (light orange line), across Meridiani Planum (dark orange line), and following the contact eastward between the Meridiani plains and uplands (brown line). All these traverses are with a 500 km radius of the LZ.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

will be impressive. The long range traverses enabled by the flat and smooth terrain will more than offset the absence of high relief and may invoke comparisons to great overland treks of terrestrial explorers. Local area of high relief, for example on the rims of craters (Fig. 24) will also provide striking backdrops to images of astronauts and their vehicles at work. Impressive but inaccessible features associated with high relief are no substitute for less impressive but accessible sites.

10.7. Common objections

It is a matter of record that the southern Meridiani candidate site for MSL/*Curiosity*, the proposed landing site for our mission, did not make it past the third landing site workshop [41]. This meeting narrowed seven candidate sites (Miyamoto crater, S Meridiani, Nili Fossae, Holden crater, Eberswalde crater, Mawrth Vallis, and Gale crater) down to four (Holden, Gale, Mawrth, and Eberswalde). South Meridiani met all of the engineering requirements but was deemed, along with Miyamoto crater, as being of lower scientific interest. It is our view that these objections do not apply to our much larger EZ. With potential exploration radius ten times greater than covered by *Curiosity* to date, a crewed landing to Meridiani would be able to meet most, possibly all, of the [73] science objectives.

Anonymous feedback provided from the first HLS^2 workshop was of value to us in writing this paper. Among the main criticisms levelled at the site were: a perceived lack of outcrop, a perception that the area was mostly Hesperian in age, and that it was visually boring.

In our view the lack of outcrop is perceived, rather than real. Numerous sections through the Hesperian Burns formation of the Meridiani plains are afforded by craters such as Endeavour and Victoria (Figs. 10 and 16). Excellent exposures of the Noachian rocks are found on the rim of Endurance crater (Figs. 13 and 22), and even flat lying areas have only shallow cover of transported regolith, allowing ready access to outcrop (e.g. Figs. 5 and 13).

The criticism that the area is dominated by Hesperian stratigraphy is only true of the northern half of the LZ. The southern half of the LZ is composed of Noachian rocks. Even in the northern plain, covered by Hesperian sediments, Noachian rocks rise through them along the rims of craters such as Miyamoto, Bopolu, and Endeavour (Fig. 15).

Visually boring is of course a subjective perception. While our LZ lacks the high relief of Gale crater or Noctis Labyrinthus, it is far from boring, with sweeping vistas (Fig. 22), craggy outcrops (Figs. 13 and 23), and textured sand seas (Figs. 9 and 14). Scientifically the spectacular cliffs of Gale crater, Vallis Marineris, or Noctis Labyrinthus are more than offset by difficulty in access due to their height and steepness (typical slopes for Vallis Marineri are up to three times higher and up to half as steep again as the Grand Canyon of Arizona or the Valley of the Indus in Ladakh, India), whereas most of the outcrops in the Meridiani EZ will be accessible by vehicle or on foot.

10.8. Precursor missions

The need for precursor missions was also discussed at the first HLS^2 workshop. In our view the success of the *Opportunity* mission may obviate the need for them. *Opportunity* in particular has provided science ground truth and trafficability data that is applicable for most of the plains and the crater rims. The crater rim data may possibly be extrapolated to the southern uplands, although this area has yet to be traversed.

If a further precursor mission is needed to be sent to the LZ, we would recommend that it consist of a scouting rover that would land in the southern uplands and, as suggested by anonymous feedback from Hays (2016, written comm.), investigate the ejecta blankets of craters such as Bopulu that might hide relict ice. The rover would also test trafficability of the Noachian uplands and scout for science features using a suite of remote science instruments (e.g. multispectral camera, VNIR spectrometer, ChemCam) and perhaps, ground penetrating radar, gravity metres, and magnetometers.

10.9. Follow-on potential

The Meridiani EZ offers access to not only diverse sites within the 100 km radius of the LZ, but targets further afield. For this reason, we included indicative ROIs beyond the 100 km radius, specifically the southwestern rim of Miyamoto crater (ROI 15) and the nearby inverted channels (ROI 19, [71,78]. Further to the northwest are the ROIs by [108] and those associated with Firsoff crater, proposed by [81]. These areas show complex history of sedimentation of both Amazonian and Hesperian age [84]. Northeast extensive traverses across Meridiani

Planum are possible, accessing units higher in the stratigraphy as well as potential Noachian outcrops uplifted in large crater rims [34,110]. Eastwards the contact between the Hesperian sediments and the Noachian plains can be followed for many hundreds of km. To the south in the Meridiani uplands lies a complex network of unnamed incised palaeodrainage, whose architecture suggests structural control. To the west is the edge of Iani Chaos [107], with its history of Hesperian to Amazonian discharge of catastrophic floods into Ares Vallis.

All these targets lie within a 500 km radius of our proposed EZ (Fig. 25), with none of the access to these areas appearing to offer substantially different trafficability to that inside of our proposal. Therefore, basing planning on experience and confidence gained in the first expedition, it is likely that these more distant ROIS and traverses could be accessed and undertaken. Pressurised vehicles proposed in [31] have endurances of up to 28 sols, with the ability to drive up 100 km per sol, all these ROIs should be readily accessible as none involve traverses of more than 1000 km.

11. Summary and conclusions

We consider the proposed Meridiani EZ an excellent candidate for the first crewed missions to Mars. The EZ is *accessible*, with near equatorial latitude allowing access from and to energy efficient near equatorial orbits. It is *safe*, due to low slopes and gradients, minimal boulders, low dust, and low altitude. The EZ contains *potential water resources* in the form of polyhydrated magnesium sulphates in the potential LZ. *Diverse science* ROIs are present, with high likelihood of meeting all Threshold and most Qualifying science goals in astrobiology, atmospheric, and geosciences. Lastly the EZ contains ROIs with *potential resources* other than water, including basalt, haematite, and regolith materials for use in civil engineering tasks, as well as providing opportunities for studying hydrothermal processes.

Additional strengths include the ability to visit hardware from previous missions. This will be of benefit to studies of materials exposed for long periods (decades) to martian conditions, assessing the effectiveness of historic planetary protection strategies, and perhaps to the general public.

Parts of the Meridiani region have been well studied from the surface by the *Opportunity*. With extensive orbital surveys in support of this mission and of the other candidate landings sites in the MER, ExoMars, and MSL programs, this will allow to take a “Go where you know” approach with respect to the Meridiani region and issues of LZ and EZ safety without reducing the potential for new science, and maximising what is known about potential resources. No matter how successful, these missions have only scratched the surface of the scientific possibilities of the region.

Lastly, beyond the immediate 100 k radius of the EZ, the Meridiani plains and uplands extend for hundreds of kilometres with few obvious issues. The area therefore offers considerable potential for much longer ranged exploration for subsequent missions. Potentially accessible regions include the southwestern rim of Miyamoto crater, Firsoff crater, northern Meridiani Planum, features of the Meridiani uplands including complex networks of structurally controlled palaeodrainage, and Iani Chaos to the west.

Objections to our proposed exploration zone following the first HLS^2 workshop suggested that the EZ suffers from lack of outcrop, consists mostly Hesperian aged rocks, and that it is visually boring. We regard these views as incorrect. Outcrop is plentiful, if subdued, the extensive Noachian exposures occur in the southern half of the EZ, and other outcrops are exposed in the rims of large craters rising through the Noachian sediments, and the sweeping vistas, craggy outcrops on crater rims, and textured sand seas are spectacular in much the same way as outback Australia. The lack of high relief is a strength, in that the rocks are accessible, unlike those of more visually impressive areas such as Noctis Labyrinthus or Vallis Marineris.

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References

[1] A. Abbud-Madrid, D.W. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L.E. Hays, J. Kleinhenz, M.A. Meyer, M. Moats, R.P. Mueller, A. Paz, N. Suzuki, P. van Susante, C. Whetsel, E.A. Zbinden, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (*m*-WIP) Study; 90 p, posted April 2016 at ⟨http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx⟩, 2016.

[2] C.C. Allen, R. Zubrin, In-situ resources, in: W.J. Larson, L.K. Pranke (Eds.), Human Spaceflight: Mission Analysis and Design., McGraw-Hill, New York, 1999, pp. 477–512.

[3] J.C. Andrews-Hanna, M.T. Zuber, R.E. Arvidson, S.M. Wiseman, Early mars hydrology: meridianimeridiani playa deposits and the sedimentary record of arabia terra, J. Geophys. Res. 115 (2010) E06002. http://dx.doi.org/10.1029/2009JE003485.

[4] R. Arvidson, D. Adams, G. Bonfiglio, P. Christensen, S. Cull, M. Golombek, J. Guinn, E. Guinness, T. Heet, R. Kirk, A. Knudson, M. Malin, M. Mellon, A. A. McEwen, A. Mushkin, T. Parker, F. F. Seelos IV, K. Seelos, P. Smith, D. Spencer, T. Stein, L. Tamppari, Mars exploration program 2007. Phoenix landing site selection and characteristics, J. Geophys. Res. 113 (2008) E00A03. http://dx.doi.org/10.1029/2007JE003021.

[5] R.E. Arvidson, R.C. Anderson, P. Bartlett, J.F. Bell, P.R. Christensen, P. Chu, K. Davis, B.L. Ehlmann, M.P. Golombek, S. Gorevan, E.A. Guinness, A.F.C. Haldemann, K.E. Herkenhoff, G. Landis, R. Li, R. Lindemann, D.W. Ming, T. Myrick, T. Parker, L. Richter, F.P. Seelos, L.A. Soderblom, S.W. Squyres, R.J. Sullivan, J. Wilson, Localization and physical property experiments conducted by opportunity at meridiani planum, Science 306 (5702) (2004) 1730–1733.

[6] R. E. Arvidson, J. W. Ashley, J. F. Bell III, M. Chojnacki, J. Cohen, T. E. Economou, W. H. Farrand, R. Fergason, I. Fleischer, P. Geissler, R. Gellert, M. P. Golombek, J. P. Grotzinger, E. A. Guinness,R. M. Haberle, K. E. Herkenhoff, J. A. Herman, K. D. Iagnemma, B. L. Jolliff, J. R. Johnson, G. Klingelhöfer, A. H. Knoll, A. T. Knudson, R. Li, S. M. McLennan, D. W. Mittlefehldt, R. V. Morris, T. J. Parker, M. S. Rice, C. Schröder, L. A. Soderblom, S. W. Squyres, R. J. Sullivan, M. J. Wolff, Opportunity Mars Rover mission: Overview and selected results from Purgatory ripple to traverses to Endeavour crater, J. Geophys. Res. 116 (2011) http://dx.doi.org/10.1029/2010JE003746

[7] ASTM International, 2015.ASTM D1241-15 Standard Specification for Materials for Soil-Aggregate Subbase, Base and Surface Courses. DOI: http://dx.doi.org/10.1520/D1241-15 Address when accessed 11/7/15 ⟨https://www.astm.org/Standards/D1241.htm⟩.

[8] D. Baker, R. Zubrin, Mars direct: combining near-term technologies to achieve a two-launch manned mars mission, J. Br. Interplanet. Soc. 43 (1990) 519–533.

[9] N.G. Barlow, What we know about Mars from its impact craters, Geol. Soc. Am. Bull. 122 (5/6) (2010) 644–657.

[10] N.G. Barlow, Central pit craters: observations from Mars and Ganymede and implications for formation models, Geol. Soc. Am. Spec. Pap. 465 (2010) 15–27.

[11] N.G. Barlow, J.M. Boyce, F.M. Costard, R.A. Craddock, J. Garvin, S.E.H. Sakimoto, R.O. Kuzmin, D.J. Roddy, S.A. Soderblom, Standardizing the nomenclature of Martian impact crater ejecta morphologies, J. Geophys. Res. 105 (Ell) (2000) 26,733–26,738.

[12] D. Beaty, P. Niles, 2015. Candidate Scientific Objectives for the Human Exploration of Mars, and Implications for the Identification of Martian Exploration Zones. Scientific Objectives for the Human Exploration of Mars Science Analysis Group. Web address when accessed 4/1/16 ⟨http://mepag.jpl.nasa.gov/reports/HSO%20summary%20presentation%20FINAL.pdf⟩

[13] M. Berggren, R. Zubrin, C. Wilson, H. Rose, S. Carrera, V. Badescu (Ed.)Mars: Propective Energy and Material Resourses, Springer-Verlag, Berlin Heidelberg, 2009. http://dx.doi.org/10.1007/978-3-642-0369-3.

[14] Bussey, B. and Hofman, S. J. 2016. Human Mars Landing Site and Impacts on Mars Surface Operations.In: Proceedings of the Conference Paper. IEEE Aerospace Conference; 37th; 5-12 Mar. 2016; Big Sky, MT; United States.

[15] S. Byrne, et al., Distribution of mid-latitude ground ice on mars from new impact craters, Science 325 (2009) 1674–1676.

[16] Casanova, I. and Aulesa, V. 2000. Construction materials from in-situ resources on the moon and mars, space 2000:In: Proceedings of the Seventh International Conference and Exposition on Engineering, Construction, Operations, and Business in Space, Albuquerque, New Mexico, United States, February 27-March 2, 2000, American Society of Civil Engineers, pp. 638-644

[17] T.C. Chamberlin, The method of multiple working hypotheses:, J. Geol. 5 (1897) 837–848.

[18] S.J. Chipera, D.T. Vaniman, J.W. Carey, 2006.Water content and dehydration behavior of Mg-sulfate hydrates. Abstracts of workshop on Martian Sulfates as

Recorders of Atmospheric-Fluid-Rock Interactions,October 22-26, LPI, Houston. Abstract 7026, address when accessed 4/1/16 ⟨http://www.lpi.usra.edu/meetings/sulfates2006/pdf/7026.pdf⟩.
[19] P.R. Christensen, Martian dust mantling and surface composition: interpretation of thermophysical properties, J. Geophys. Res. 87 (1982) 9985–9998.
[20] P.R. Christensen, M.B. Wyatt, T.D. Glotch, A.D. Rogers, S. Anwar, R.E. Arvidson, J.L. Bandfield, D.L. Blaney, C. Budney, W.M. Calvin, A. Fallacaro, R.L. Fergason, N. Gorelick, T.G. Graff, V.E. Hamilton, A.G. Hayes, J.R. Johnson, A.T. Knudson, H.Y. McSween, G.L. Mehall, L.K. Mehall, J.E. Moersch, R.V. Morris, M.D. Smith, S.W. Squyres, S.W. Ruff, M.J. Wolff, Mineralogy at meridiani planum from the mini-tesmini-tes experiment on the opportunity rover, Science 306 (5702) (2004) 1733–1739.
[21] B.C. Clark, R.V. Morris, S.M. McLennan, R. Gellert, B. Jolliff, A.H. Knoll, S.W. Squyres, T.K. Lowenstein, D.W. Ming, N.J. Tosca, A. Yen, P.R. Christensen, S. Gorevan, J. Brückner, W. Calvin, G. Dreibus, W. Farrand, G. Klingelhoefer, H. Waenke, J. Zipfel, J.F. Bell, J. Grotzinger, H.Y. McSween, R. Rieder, Chemistry and mineralogy of outcrops at Meridiani Planum, Earth Planet. Sci. Lett. 240 (1) (2005) 73–94.
[22] Clarke, J. D. A., Willson, D., and Cooper, D. 2010. In-situ resource utilisation through water extraction from hydrated minerals – relevance to Mars missions and an Australian analogue.In: Proceedings of the 6th Australians Mars Exploration Conference, Melbourne 2006. Mars Society Australia. Web address when accessed 4/1/16 http://old.marssociety.org.au/library/coober_pedy_ISRU_AMEC.pdf.
[23] J.D.A. Clarke, D. Willson, H.D. Smith, 2015.First Landing: Southern edge of meridiani planum abstracts. In: Proceedings of the First Landing Site (LS)/ Exploration Zone (EZ) Workshop for Human Missions to the Surface of Mars, Lunar and Planetary Institute, Houston, Abstract #1057. Web address when accessed 4/1/16 ⟨http://www.hou.usra.edu/meetings/explorationzone2015/pdf/1057.pdf⟩.
[24] C.S. Cockell, P. Lee, G. Osinski, G. Horneck, P. Broady, Impact-induced microbial endolithic habitats, Meteorit. Planet. Sci. 37 (10) (2002) 1287–1298.
[25] B.A. Cohen, M.A. Seibert, The land of opportunity: human return to meridiani planum. abstracts. In: Proceedings of the First Landing Site (LS)/Exploration Zone (EZ) Workshop for Human Missions to the Surface of Mars, Lunar and Planetary Institute, Houston, Abstract #1030. Web address when accessed 4/1/16 ⟨http://www.hou.usra.edu/meetings/explorationzone2015/pdf/1030.pdf⟩, 2015.
[26] COSPAR, Cospar Planetary Protection Policy. Address when accessed 28/3/16 ⟨http://w.astro.berkeley.edu/~kalas/ethics/documents/environment/COSPAR%20Planetary%20Protection%20Policy.pdf⟩, 2005.
[27] I. Crawford, Dispelling the myth of robotic efficiency, Astron. Geophys. 53 (2012) 22–26.
[28] L.S. Crumpler, R.E. Arvidson, J. Bell, B.C. Clark, B.A. Cohen, W.H. Farrand, R. Gellert, M. Golombek, J.A. Grant, E. Guinness, K.E. Herkenhoff, J.R. Johnson, B. Jolliff, D.W. Ming, D.W. Mittlefehldt, T. Parker, J.W. Rice Jr., S.W. Squyres, R. Sullivan, A.S. Yen, Context of ancient aqueous environments on Mars from in situ geologic mapping at endeavour crater, J. Geophys. Res.: Planets 120 (3) (2015) 538–569.
[29] B.G. Drake (Ed.)Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team, NASA NASA/SP—6107–ADD, 1998, p. 50.
[30] B.G. Drake (Ed.)Human Exploration of Mars Design Reference Architecture 5.0, NASA/SP–2009–566, 2009, p. 83.
[31] B.G. Drake (Ed.)Human Exploration of Mars Design Reference Architecture 5.0 Addendum-ADD, NASA/SP–2009–566, 2014, p. 383.
[32] P. Duhem, The Aim and Structure of Physical Theory, trans. And reprinted, Princeton University Press, Princeton, N.J., 1954 (1954).
[33] M.B. Duke (Ed.)Workshop on using in situ resources for construction of planetary outposts, Lunar and Planetary Institute Technical Report Number 98-01, 1998.
[34] K.S. Edgett, The sedimentary rocks of sinus Meridiani: five key observations from data acquired by the mars global surveyor and mars odyssey orbiters, Int. J. Mars Sci. Explor. 1 (2005) 5–58. http://dx.doi.org/10.1555/mars.2005.0002.
[35] R.L. Fergason, P.R. Christensen, J.F. Bell, M.P. Golombek, K.E. Herkenhoff, H.H. Kieffer, Physical properties of the mars exploration rover landing sites as inferred from Mini-TES—Derived thermal inertia, J. Geophys. Res. 111 (2006) 1–18.
[36] J. Flahaut, J. Carter, F. Poulet, J.-P. Bibring, W. van Westrenen, G.R. Davies, S.L. Murchie, Embedded clays and sulfates in Meridiani Planum, Mars Icarus 248 (2015) 269–288.
[37] I.L. Freeman, Mineralogy of ten British brick clays, Clay Miner. Bull. 5 (1964) 474–496.
[38] P.E. Geissler, R. Sullivan, M. Golombek, J.R. Johnson, K. Herkenhoff, N. Bridges, A. Vaughan, J. Maki, T. Parker, J. Bell, Gone with the wind: Eolian erasure of the Mars Rover tracks, J. Geophys. Res. 115 (E12) (2010). http://dx.doi.org/10.1029/2010JE003674.
[39] Gendrin, et al., Sulfates in martian layered terrains:terrains the: the omega/marsomega/mars express view, Science 307 (2005) 1587–1591.
[40] D.P. Glavin, J.P. Dworkin, M. Lupisella, G. Kminek, J.D. Rummel, Biological contamination studies of lunar landing sites: implications for future planetary protection and life detection on the Moon and Mars, Int. J. Astrobiol. 3 (3) (2004) 265–271.
[41] M. Golombek, J. Grant, D. Kipp, A. Vasavada, R. Kirk, R. Fergason, P. Bellutta, F. Calef, K. Larsen, Y. Katayama, A. Huertas, R. Beyer, A. Chen, T. Parker, B. Pollard, S. Lee, Y. Sun, R. Hoover, H. Sladek, J. Grotzinger, R. Welch, E. Noe Dobrea, J. Michalski, M. Watkins, Selection of the Mars Science laboratory landing site, Space Sci. Rev. 170 (1) (2012) 641–737.
[42] M.P. Golombek, A. Huertas, J. Marlow, B. McGrane, C. Klein, M. Martinez, R.E. Arvidson, T. Heet, L. Barry, K. Seelos, et al., Size-frequency distributions of rocks on the northern plains of Mars with special reference to phoenix landing surfaces, J. Geophys. Res. 113 (2008) 1–32.
[43] M.P. Golombek, J.A. Grant, T.J. Parker, D.M. Kass, J.A. Crisp, S.W. Squyres, A.F.C. Haldemann, M. Adler, W.J. Lee, N.T. Bridges, R.E. Arvidson, M.H. Carr, R.L. Kirk, P.C. Knocke, R.B. Roncoli, C.M. Weitz, J.T. Schofield, R.W. Zurek, P.R. Christensen, R.L. Fergason, F.S. Anderson, J.W. Rice, Selection of the mars exploration rover landing sites, J. Geophys. Res. 108 (E12) (2003) 8072.
[44] Golombek, M.P., Huertas, A., Marlow, J., McGrane, B., Klein, C., Martinez, M., Arvidson, R.E., Heet, T., Barry, L., Seelos, K., et al. 2008. Size-frequency distributions of rocks on the northern plains of Mars with special reference to Phoenix landing surfaces. Journal Geophysical Research 113, 1–32.Grant, J. A., Crumpler, L. S., Parker, T. J., Golombek, M. P., Wilson, S. A., and Mittlefehldt, D. W. 2015. Degradation of Endeavour Crater, Mars. Icarus, in press
[45] J.A. Grant, M.P. Golombek, J.P. Grotzinger, S.A. Wilson, M.M. Watkins, A.R. Vasavada, J.L. Griffes, T.J. Parker, The science process for selecting the landing site for the 2011 Mars Science laboratory, Planet. Space Sci. 59 (11–12) (2010) 1114–1127.
[46] K.K. de Groh, B.A. Banks, Atomic-oxygen undercutting of Long duration exposure facility atomized-Kapton multilayer insulation, J. Spacecr. Rockets 31 (4) (1994) 656–664.
[47] J.P. Grotzinger, R.E. Arvidson, J.F. Bell, W. Calvin, B.C. Clark, D.A. Fike, M. Golombek, R. Greeley, A. Haldemann, K.E. Herkenhoff, B.L. Jolliff, A.H. Knoll, M. Malin, S.M. McLennan, T. Parker, L. Soderblom, J.N. Sohl-Dickstein, S.W. Squyres, N.J. Tosca, W.A. Watters, Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars, Earth Planet. Sci. Lett. 240 (1) (2005) 11–72.
[48] Hare, T.M., Cushing, G., Shinamen, J., Day, B., and Law, E. 2016. Context Camera (CTX) Image Mosaics for Mars Human Exploration Zones, Astrogeology, U.S. Geological Survey, Address when accessed 16/7/16 http://bit.ly/CTX_EZs
[49] K.E. Herkenhoff, M.P. Golombek, E.A. Guinness, J.B. Johnson, A. Kusack, L. Richter, R.J. Sullivan, S. Gorevan, In situ observations of the physical properties of the Martian surface, in: J. Bell (Ed.)The Martian Surface: Composition, Mineralogy and Physical Properties., Cambridge University Press, Cambridge, UK, 2008, pp. p451–p467.
[50] S.J. Hoffman (Ed.)The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities, NASA Technical Publication NASA/TP—2001–209371, 2001, p. 89.
[51] S.J. Hoffman, 2015.ISRU & Civil Engineering Needs for Future Human Mars Missions. Address when accessed ⟨http://mepag.nasa.gov/reports/HLS2%20briefing%2027Oct15%20ICEWG%20v2.pdf⟩ (presentation only).
[52] G. Horneck, H. Bücker, G. Reitz, Long-term survival of bacterial spores in space, Adv. Space Res. 14 (10) (1994) 41–45.
[53] S. Hubbard, Exploring Mars: Chronicles from A Decade of Discovery, University of Arizona Pressm, 2012, p. 224.
[54] B.M. Hynek, R.J. Phillips, Evidence for extensive denudation of the Martian highlands, Geology 29 (5) (2001) 407–410.
[55] iMARS, 2006. Preliminary Planning for an International Mars Sample Return Mission, Report of the International Mars Architecture for the Return of Samples (iMARS) Working Group, June 1, 2008. Address when accessed 6/11/16 ⟨http://mepag.nasa.gov/reports/iMARS_FinalReport.pdf⟩.
[56] R.P. Irwin III, A.D. Howard, R.A. Craddock, J.M. Moore, An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development, J. Geophys. Res. 110 (2005) E12S15. http://dx.doi.org/10.1029/2005JE00246.
[57] G. James, G. Chamitoff, D. D. Barker, Resource utilization and site selection for a self-sufficient martian outpost, NASA NASA/TM-98-206538 (1998).
[58] E. Jones, G. Caprarelli, F. Mills, B. Doran, J. Clarke, An alternative approach to mapping thermophysical units from martian thermal inertia and albedo data using a combination of unsupervised classification techniques, Remote Sens. 6 (2014) 5184–5237.
[59] JORC, 2012.The JORC Code2012. Prepared by the Join Ore Reserves Committee of the Australian Asian Institute of Mining and Metallurgy, Australian Insitute of Geociences, and the Minerals Council of Australia (JORC) ⟨http://www.jorc.org/docs/jorc_code2012.pdf⟩.
[60] S.J. Kadish, J.W. Head, N.G. Barlow, Pedestal crater heights on Mars: a proxy for the thicknesses of past, ice-rich, Amazonian deposits, Icarus 210 (2010) 92–101.
[61] C.M. Katzan, C.R. Stidham, 1991.Lunar dust interactions with photovoltaic arrays. In: Proceedings of the Photovoltaic Specialists Conference, 7-11 Oct 1991, Conference Record of the Twenty Second IEEE, vol.2, 1548–1553.
[62] H.H. Kieffer, S.C. Chase, E. Miner, G. Münch, G. Neugebauer, Preliminary report on infrared radiometric measurements from the Mariner 9 spacecraft, J. Geophys. Res. 78 (20) (1973) 4291–4312.
[63] R.L. Kirk, L.A. Soderblom, G. Cushing, T.A. Tituus, Joint analysis of visible and infrared images: a "magic airbrush" for qualitative and quantitative topography, Photogramm. Eng. Remote Sens. J. 71 (2005) 1167–1178.
[64] A.H. Knoll, M. Carr, B. Clark, D.J. Des Marais, J.D. Farmer, W.W. Fischer, J.P. Grotzinger, S.M. McLennan, M. Malin, C. Schröder, S. Squyres, N.J. Tosca, T. Wdowiak, An astrobiological perspective on meridiani planum, Earth Planet. Sci. Lett. 240 (1) (2005) 179–189.
[65] J.E. Kogel, N.C. Traverdi, J.M. Barker, S.T. Krukowski (Eds.), Industrial Minerals & Rocks: Commodities, Markets, and Uses, Society for Mining, Metallurgy, and Exploration Inc., Littleton, Colorado, 2006, p. 1548.
[66] D. Kontogeorgos, I. Mandilaras, M. Founti, Temperatures Scrutinizing Gypsum

Board Thermal Performance at Dehydration, Journal of Fire Sciences 29 (2011) 111–130.
[67] Landis, G.A., and the MER ATHENA Science team. 2007. Observation of frost at the equator of Mars by the Opportunity rover. Abstracts 38th Lunar and Planetary Science Conference Abstract 2423
[68] L. Levrard, F. Forget, Montmessin, J. Laskar, Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity, Nature 431 (2004) 1072–1075.
[69] LPI, First landing site/exploration zone workshop for human missions to the surface of mars supplemental paper, Lunar and Planetary Institute, Houston, 2015 (Web address when accessed 5/1/16) ⟨http://www.hou.usra.edu/meetings/explorationzone2015/program_presenter_info/Supplemental%20_Paper.pdf⟩.
[70] J. Martín-Torres, M.-P. Zorzano, P. Valentín-Serrano, A.-M. Harri, M. Genzer, et al., Transient liquid water and water activity at Gale crater on Mars, Nat. Geosci. 8 (2015) 357–361.
[71] G.A. Marzo, T.L. Roush, N.L. Lanza, P.C. McGuire, H.E. Newsom, A.M. Ollila, S.M. Wiseman, Association of phyllosilicates and the inverted channel in Miyamoto crater, Mars, Geophys. Res. Lett. 36 (11) (2009) L11204.
[72] M.T. Mellon, R.L. Fergason, N.E. Putzig, The thermal inertia of the surface of Mars, in: J. Bell (Ed.)The Martian Surface: Composition, Mineralogy, and Physical Properties., Cambridge University Press, Cambridge, UK, 2008, pp. 399–427.
[73] MEPAG, Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015. V. Hamilton, ed., 74 p. white paper posted June 2015 by the Mars Exploration Program Analysis Group (MEPAG) address when accessed 5/1/16 ⟨http://mepag.nasa.gov/reports.cfm⟩, 2015.
[74] P.T. Metzger, X. Li, C.D. Immer, J.E. Lane, 2009.SRU Implications for Lunar and Martian Plume Effects. Proceedings of the 47th AIAA Aerospaces Sciences Meeting, 5–8 January 2009, Orlando, Florida, AIAA 2009–1204.
[75] T.R. Meyer, C.P. McKay, Using the resources of mars for human settlement, in: C.R. Stoker, C. Emmart. (Eds.), Strategies for Mars: A Guide to Human Exploration, *A*merican Astronautical Society, San Diego, CA, 1996 (Chapter 19).
[76] R.W. Moses, D.M. Bushnell, Frontier In-Situ Resource Utilization for Enabling Sustained Human Presence on Mars, NASA Technical Memorandum TM–2016-219182, 2016.
[77] Mustard, J. F., Adler, M., Allwood, A., Bass, D. S., Beaty, D. W., Bell, J. F. III, Brinckerhoff, W. B., Carr, M., Des Marais, D. J., Drake, B., Edgett, K. S., Eigenbrode, J., Elkins-Tanton, L. T., Grant, J. A., Milkovich, S. M., Ming, D., Moore, D., Murchie, S., Onstott, T. C., Ruff, S. W., Sephton, M. A., A. Steele, A., and Treiman, A. 2013. Report of the Mars 2020 Science Definition Team. 154 pp., posted July, 2013, by the Mars Exploration Program Analysis Group (MEPAG). Address when accessed 12/7/16 http://mepag.nasa.gov/reports/MEP/Mars_2020_SDT_Report_Final.pdf
[78] H.E. Newsom, N.L. Lanza, A.M. Ollila, S.M. Wiseman, T.L. Roush, G.A. Marzo, L.L. Tornabene, C.H. Okubo, M.M. Osterloo, V.E. Hamilton, L.S. Crumpler, Inverted channel deposits on the floor of Miyamoto crater, Mars, Icarus 205 (1) (2010) 64–72.
[79] E.Z. Noe Dobrea, J.J. Wray, F.J. Calef III, T.J. Parker, S.L. Murchie, Hydrated minerals on Endeavour Crater's rim and interior, and surrounding plains: new insights from CRISM data, Geophys. Res. Lett. 39 (23) (2012) L23201.
[80] S.A. Nowicki, P.R. Christensen, Rock abundance on Mars from the thermal emission spectrometer, J. Geophys. Res. 112 (E5) (2007) 1–20.
[81] Ori, G. G. and Pondrelli, M. 2015. Exploration Zone for Human mission to Mars: the area South of Firsoff Crater in Arabia Terra. Abstracts of the First Landing Site (LS)/Exploration Zone (EZ) Workshop for Human Missions to the Surface of Mars, Lunar and Planetary Institute, Houston, Abstract #1026. Web address when accessed 4/1/16 http://www.hou.usra.edu/meetings/explorationzone2015/pdf/1026.pdf
[82] Ori, G. G., Aboudan, A., Portigliotti, S., Marcer, A., Lorenzoni, L., Pacifici, A., and Cannarsa, F. 2014. The Analysis of the ExoMars 2016 Landing Site. 45th Lunar and Planetary Science Conference, Abstract 1787
[83] Pacifici, A., Ori, G. G., Cannarsa, F., Murana, A., Aboudan, A., Portigliotti, S., Marcer, A., and Lorenzoni, L. 2014. Geological and Geomorphological Map of ExoMars 2016 Landing Site. 45th Lunar and Planetary Science Conference, Abstract 1531
[84] M. Pondrelli, A.P. Rossi, L. Le Deit, F. Fueten, S. van Gasselt, M. Glamoclija, B. Cavalazzi, E. Hauber, F. Franchi, R. Pozzobon, Equatorial layered deposits in Arabia Terra, Mars:, Facies Process Var. Geol. Soc. Am. Bull. 127 (7/8) (2015) 1064–1089.
[85] Popper, K. 1959. The Logic of Scientific Discovery. English translation 1959, republished 2002 by Routledge 2002, p. 544
[86] Portigliotti, S., Dumontel, M., Capuano, M., and Lorenzoni, L. 2010. Landing site targeting and constraints for ExoMars 2016 mission.In: Proceedings of the 7th International Planetary Probe Workshop, Barcelona, Space, 14-18th June 2010
[87] H. Price, J. Baker, F. Naderi, A minimal architecture for human journeys to Mars, New Space 3 (2) (2015) 73–81.
[88] N.E. Putzig, M.T. Mellon, Thermal behavior of horizontally mixed surfaces on Mars, Icarus 191 (1) (2007) 52–67.
[89] Raftery, M., Cooke, D., Hopkins, J., and Hufenbach, B. 2013 An affordable mission to Mars.In: Proceedings of the 64th International Astronautical Congress, Beijing, China. IAC-13,A5,4-D2.8, 7p.
[90] R. Rieder, R. Gellert, R.C. Anderson, J. Brückner, B.C. Clark, G. Dreibus, T. Economou, G. Klingelhöfer, G.W. Lugmair, D.W. Ming, S.W. Squyres, C. d'Uston, H. Wänke, A. Yen, J. Zipfel, Chemistry of rocks and soils at meridiani planum from the alpha particle x-rayx-ray spectrometer, Science 306 (5702) (2004) 1746–1749.
[91] A.D. Rogers, O. O. Aharonson, Mineralogical composition of sands in meridiani planum determined from mars explorationexploration rover data and comparison to orbital measurements, J. Geophys. Res. 113 (2008) E06S14. http://dx.doi.org/10.1029/2007JE002995.
[92] S.P. Schwenzer, D.A. Kring, Impact-generated hydrothermal systems capable of forming phyllosilicates on Noachian Mars, Geology 37 (12) (2009) 1091–1094.
[93] S. Silvestro, D.A. Vaz, G.D. Di Achille, I.C. Popa, F. Esposito, Evidence for different episodes of aeolian construction and a new type of wind streak in the 2016 ExoMars landing ellipse in meridiani planum, Mars, J. Geophys. Res. Planets 120 (2015). http://dx.doi.org/10.1002/2014JE004756.
[94] Smithers Apex 2016. Global gypsum market set for 9.9% growth. Web address when accessed 16/1/16 < http://www.smithersapex.com/news/2016/february/global-gypsum-market-set-for-growth > .
[95] L.A. Soderblom, R.C. Anderson, R.E. Arvidson, J.F. Bell, N.A. Cabrol, W. Calvin, P.R. Christensen, B.C. Clark, T. Economou, B.L. Ehlmann, W.H. Farrand, D. Fike, R. Gellert, T.D. Glotch, M.P. Golombek, R. Greeley, J.P. Grotzinger, K.E. Herkenhoff, D.J. Jerolmack, J.R. Johnson, B. Jolliff, G. Klingelhöfer, A.H. Knoll, Z.A. Learner, R. Li, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, R.V. Morris, J.W. Rice, L. Richter, R. Rieder, D. Rodionov, C. Schröder, F.P. Seelos, J.M. Soderblom, S.W. Squyres, R. Sullivan, W.A. Watters, C.M. Weitz, M.B. Wyatt, A. Yen, J. Zipfel, Soils of eagle crater and meridiani planum at the opportunity rover landing site, Science 306 (5702) (2004) 1723–1726.
[96] S.W. Squyres, A.H. Knoll, Sedimentary rocks at meridiani planum:planum: origin,origin, diagenesis, and implications for life on Mars, Earth Planet. Sci. Lett. 240 (1) (2005) 1–10.
[97] S.W. Squyres, R.E. Arvidson, J.F. Bell, F. Calef, B.C. Clark, B.A. Cohen, L.A. Crumpler, P.A. de Souza, W.H. Farrand, R. Gellert, J. Grant, K.E. Herkenhoff, J.A. Hurowitz, J.R. Johnson, B.L. Jolliff, A.H. Knoll, R. Li, S.M. McLennan, D.W. Ming, D.W. Mittlefehldt, T.J. Parker, G. Paulsen, M.S. Rice, S.W. Ruff, C. Schröder, A.S. Yen, K. Zacny, Ancient impact and aqueous processes at endeavour crater,crater, Mars, Science 336 (6081) (2012) 570–576.
[98] S.W. Squyres, R.E. Arvidson, J.F. Bell, J. Brückner, N.A. Cabrol, W. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W. Farrand, W. Folkner, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, L. Haskin, K.E. Herkenhoff, S. Hviid, J. Johnson, G. Klingelhöfer, A.H. Knoll, G. Landis, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice, L. Richter, R. Rieder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, H. Wänke, T. Wdowiak, M. Wolff, A. Yen, The opportunity Rover's Athena Science investigation at meridiani planum,planum, Mars, Science 306 (5702) (2004) 1698–1703.
[99] S.W. Squyres, R.E. Arvidson, D. Bollen, J.F. Bell, J. Brückner, N.A. Cabrol, W.M. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W.H. Farrand, W. Folkner, R. Gellert, T.D. Glotch, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, K.E. Herkenhoff, S. Hviid, J.R. Johnson, G. Klingelhöfer, A.H. Knoll, G. Landis, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice, L. Richter, R. Rieder, C. Schröder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, N.J. Tosca, H. Wänke, T. Wdowiak, M. Wolff, A. Yen, Overview of the opportunity mars exploration rover mission to meridiani planum:planum: eagle crater to purgatory ripple, J. Geophys. Res. 111 (2006) E12s12. http://dx.doi.org/10.1029/2006JE002771.
[100] C.R. Stoker, J.L. Gooding, T. Roush, A. Banin, D. Burt, B.C. Clark, G. Flynn, O. Gwynne, The physical and chemical properties and research potential of martian surface soils (1993), in: J.S. Lewis, M.S. Matthews, M.L. Guerrieri (Eds.), Resources of Near Earth Space, University of Arizona Press, Tucson, 1993, pp. p659–p707.
[101] R. Sullivan, R. Anderson, J. Biesiadecki, T. Bond, H. Stewart, Cohesions, friction angles, and other physical properties of Martian regolith from Mars exploration Rover wheel trenches and wheel scuffs, J. Geophys. Res. 116 (2011) E02006. http://dx.doi.org/10.1029/2010JE003625.
[102] R. Sullivan, D. Banfield, J.F. Bell, W. Calvin, D. Fike, M. Golombek, R. Greeley, J. Grotzinger, K. Herkenhoff, D. Jerolmack, M. Malin, D. Ming, L.A. Soderblom, S.W. Squyres, S. Thompson, W.A. Watters, C.M. Weitz, A. Yen, Aeolian processes at the Mars exploration rover meridiani planum landing site, Nature 436 (7047) (2005) 58–61.
[103] M. Thomas, J.D.A. Clarke, C.F. Pain, Weathering, erosion and landscape processes on Mars identified from recent rover imagery, and possible Earth analogues, Aust. J. Earth Sci. 52 (3) (2005) 365–378.
[104] N.J. Tosca, A.H. Knoll, S.M. McLennan, Water activity and the challenge for life on early Mars, Science 320 (2008) 1204–1207. http://dx.doi.org/10.1126/science.1155432.
[105] L. Toups, S.J. Hoffman, K. Watts, 2016.Mars surface systems common capabilities and challenges for human missions.In: Proceedings of the Conference Paper IEEE Aerospace Conference 5-12 Mar, 2016; Big Sky, MT; United States.
[106] D. Waller, Active Dust Devils on Mars: Aa Comparison of Six Spacecraft Landing Sites (M.S. Thesis), Arizona State University, United States, 2011.
[107] N.H. Warner, S. Gupta, J.-R. Kim, J.-P. Muller, L. Le Corre, J. Morley, S.-Y. Lin, C. McGonigle, Constraints on the origin and evolution of Iani Chaos, Mars, J. Geophys. Res. 116 (2011) E06003. http://dx.doi.org/10.1029/2010JE003787.
[108] M.J. Wilkinson, P.J. McGovern, Sinus Meridiani Landing Site for Human Exploration—A Mesoscale Fluvial System. Abstracts of the First Landing Site (LS)/Exploration Zone (EZ) Workshop for Human Missions to the Surface of Mars, Lunar and Planetary Institute, Houston, 2015 (Abstract #1042. Web address when accessed 4/1/16) ⟨http://www.hou.usra.edu/meetings/

explorationzone2015/pdf/1042.pdf⟩.
[109] Willson, D. and Clarke, J. 2007. A practical architecture for exploration-focused manned mars missions using chemical propulsion, solar power generation and in-situ resource utilisation.In: Proceedings of the 6th Australian Space Science Conference. Address when accessed 4/1/16 http://www.nssa.com.au/6assc/downloads/6assc%20proceedings.pdf
[110] S.M. Wiseman, Spectral and Stratigraphic Mapping of Hydrated Sulfate and Phyllosilicate-bearing Deposits: implications for the Aqueous History of Sinus Meridiani, Mars (PhD Thesis), Washington University, St Louis, 2009 (PhD Thesis) ⟨http://openscholarship.wustl.edu/cgi/viewcontent.cgi?article=1377&context=etd⟩.
[111] Wiseman, S. M., Arvidson, R. E., and Mustard, J. F. 2012. Sinus Meridiani and Arabia Terra: phyllosilicate and sulfate stratigraphy.In: Proceedings of the Abstracts Third International Conference on Early Mars, Lake Tahoe, Nevada, Abstract 7061, address when accessed 4/1/16 http://www.lpi.usra.edu/meetings/earlymars2012/pdf/7061.pdf
[112] S.M. Wiseman, R.E. Arvidson, J.C. Andrews-Hanna, R.N. Clark, N.L. Lanza, D. Des Marais, G.A. Marzo, R.V. Morris, S.L. Murchie, H.E. Newsom, E.Z. Noe Dobrea, A.M. Ollila, F. Poulet, T.L. Roush, F.P. Seelos, G.A. Swayze, Phyllosilicate and sulfate-hematite deposits within Miyamoto crater in southern sinus Meridiani, Mars, Geophys. Res. Lett. 35 (19) (2008) L19204.
[113] J.J. Wray, E.Z. Noe Dobrea, R.E. Arvidson, S.M. Wiseman, S.W. Squyres, A.S. McEwen, J.F. Mustard, S.L. Murchie, Phyllosilicates and sulfates at Endeavour Crater, Meridiani Planum, Mars, Geophys. Res. Lett. 36 (2009) L21201. http://dx.doi.org/10.1029/2009GL040734.
[114] A. Zent, A historical search for habitable ice at the Phoenix landing site, Icarus 196 (2008) 385–408.
[115] R. Zubrin, D. Weaver, 1993.Practical methods for near-term piloted Mars missions.In: Proceedings of the AIAA, SAE, ASME, and ASEE Joint Propulsion Conference and Exhibit, 29th, Monterey, CA, June 28-30, p. 20.